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13. ABSTRACT (Maximum 200 words) WES WAS AUTHORIZED BY RMA TO INSTALL FIVE TEST WELLS AND RELATED OBSERVATION WELLS OR PIEZOMETERS AND CONDUCT PUMPING TEST ON EACH OF THE TEST WELLS. THE FIVE WELLS WERE INSTALLED AND DEVELOPED DURING THE PERIOD OF 16-23 MARCH 1978. ONE PUMPING TEST WAS CONDUCTED DURING THE PERIOD 5-10 APRIL 1978; THE REMAINING FOUR DURING 12 JUNE - 10 JULY 1978. THIS REPORT DESCRIBES THE WELL INSTALLATION, CONDUCT OF THE PUMPING TESTS AND RESULTS OF THE ANALYSES OF EACH TEST.				
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REPORT OF FINDING

ROCKY MOUNTAIN ARSENAL
PUMPING TESTS

by
Mark A. Vispi

September 1978

Rocky Mountain Arsenal
Information Center
Commerce City, Colorado

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Rocky Mountain Arsenal
Installation Restoration Program

Conducted by

U. S. Army Engineer Waterways Experiment Station
Corps of Engineers
Vicksburg, Mississippi

PREFACE

Five field pumping tests were conducted in the Basin F - North area at the Rocky Mountain Arsenal, Denver, CO. The work was accomplished for and in support of the Installation Restoration Program for the Rocky Mountain Arsenal as specified in the FY 78 Statement of Work dated November 1977, Item 1.05.63 Task III. The work was performed by the Explorations Branch, Engineering Geology and Rock Mechanics Division (EGRMD), Geotechnical Laboratory, U. S. Army Engineer Waterways Experiment Station (WES). This report describes the well installations, conduct of the pumping tests, and results of the analyses of each test.

Well installation and development was performed under the direction of Mr. Joe L. Gatz. Field pumping tests were conducted under the direction of Mr. Mark A. Vispi, assisted by Mr. Robert David Bennett of the Design Investigations Branch, EGRMD. Mr. Bennett also assisted Mr. Vispi in the reduction of field data and in the analysis of the tests. This report was prepared by Mr. Vispi.

Commander and Director of WES during the conduct of this project was COL John L. Cannon, CE. Technical Director was Mr. F. R. Brown.

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Rocky Mountain Arsenal Pumping Tests

1. The Exploration Branch, Geotechnical Laboratory, U. S. Army Engineer Waterways Experiment Station (WES), was authorized by the Rocky Mountain Arsenal (RMA) to install five test wells and related observation wells or piezometers and conduct pumping tests on each of the test wells. The five test wells were installed and developed during the period 16-23 March 1978. One pumping test was conducted during the period 5-10 April 1978; the remaining four pumping tests were conducted during the period 12 June - 10 July 1978.

2. All five wells were located by RMA personnel in Sections 23 and 24 of the arsenal. Figure 1 shows the general locations of the wells. Figures 2 through 6 show the "as constructed" well installations. All wells extended down to weathered bedrock. In all cases, the screen portion of the well extends through the bottom three-quarters of the saturated aquifer as a minimum. In all the tests the water level was drawn down sufficiently so that it was within the screened portion of the well.

3. All wells were installed using a Failing Model 1500 truck-mounted drill rig and were drilled using the conventional rotary drilling methods with a 7-3/4-in.-diam tricone roller bit and self-destructing organic drilling fluid (Johnson's Revert). Five-inch-diameter Johnson PVC wrap, continuous slot screen was installed in all wells. The slot size varied from well to well depending on the aquifer grain size at the well location. The screen slot size for each well was determined from grain size distribution curves of samples taken from the aquifer at the

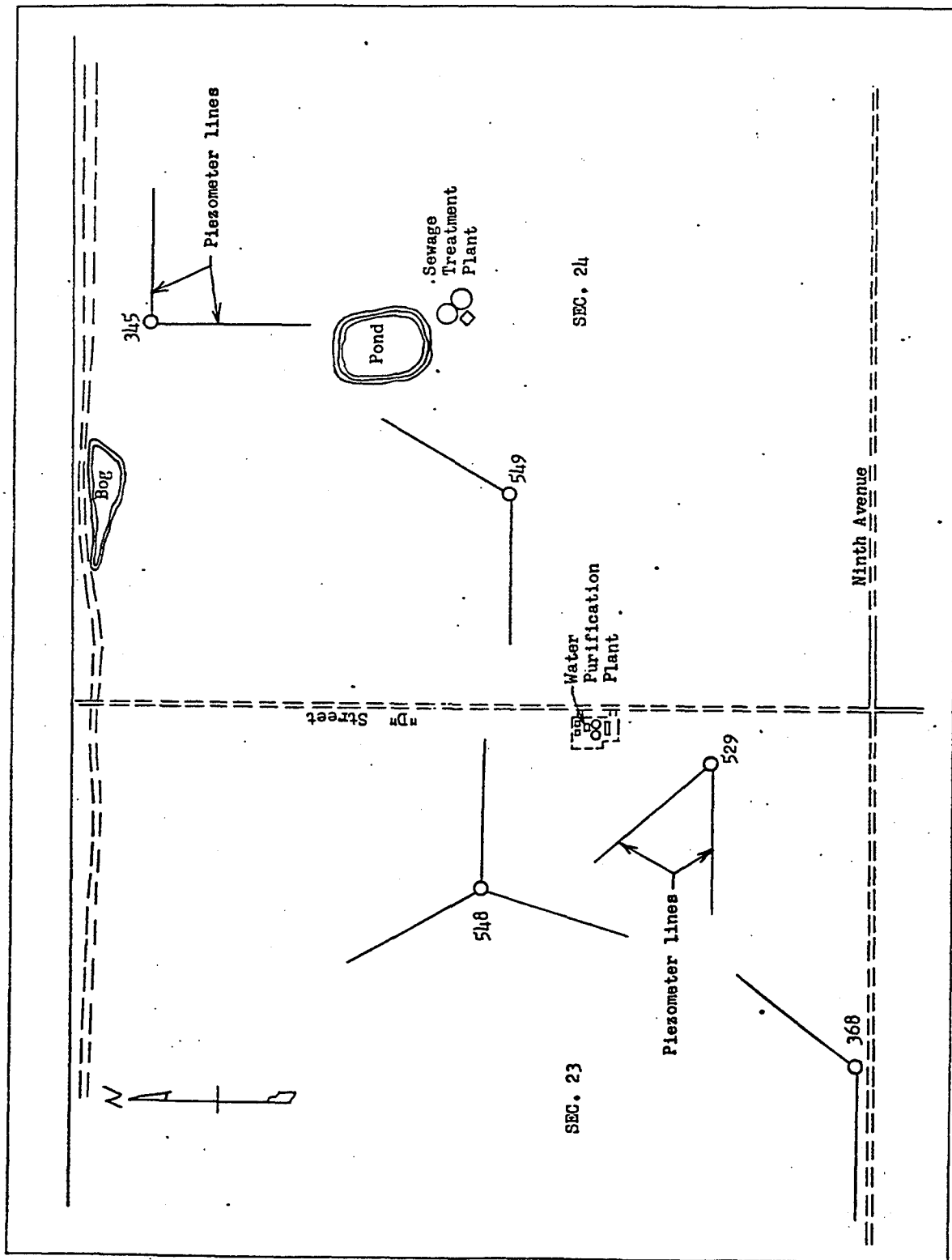


Figure 1. Test Well Locations

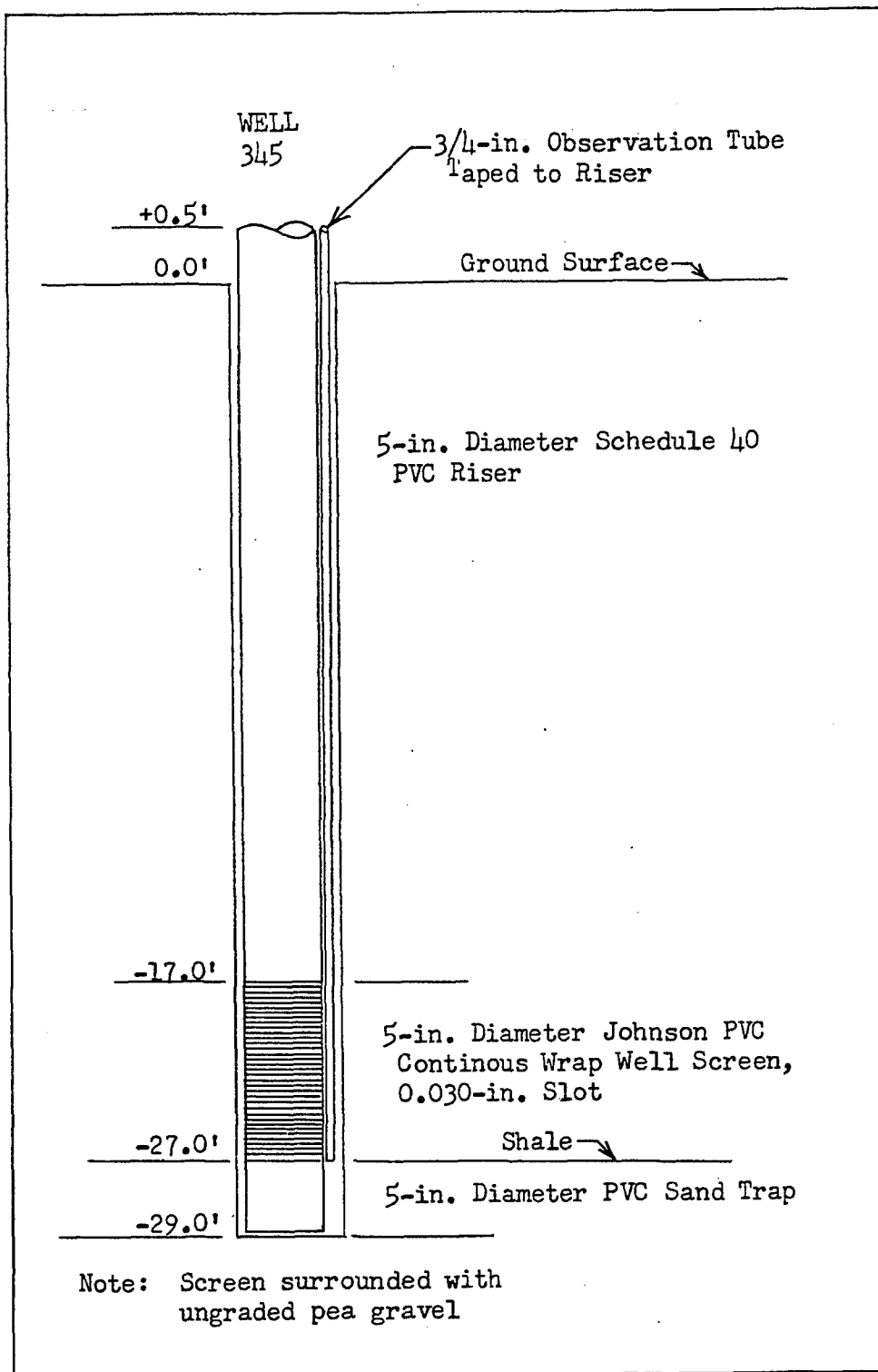


Figure 2. Test Well 345

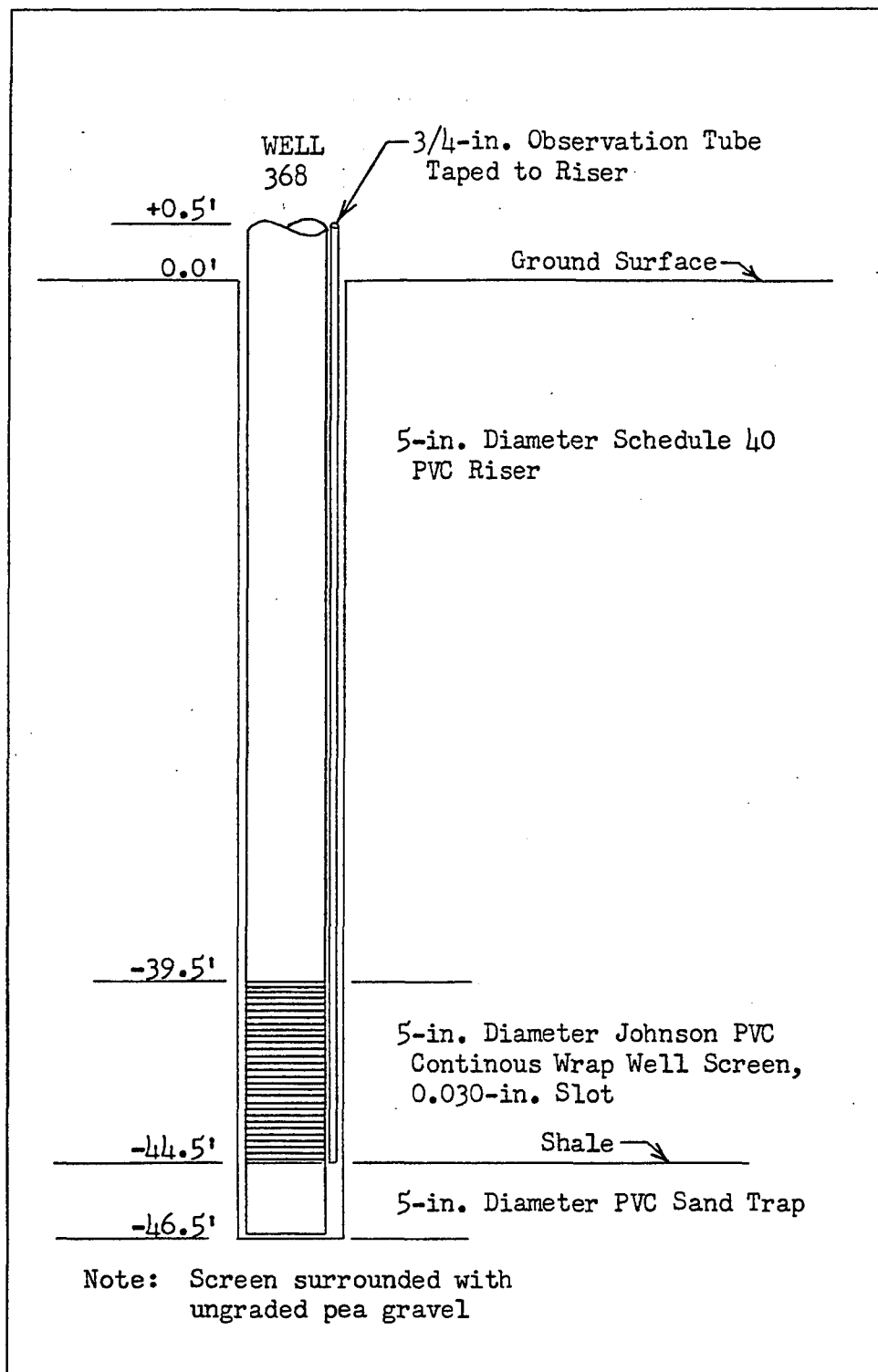


Figure 3. Test Well 368

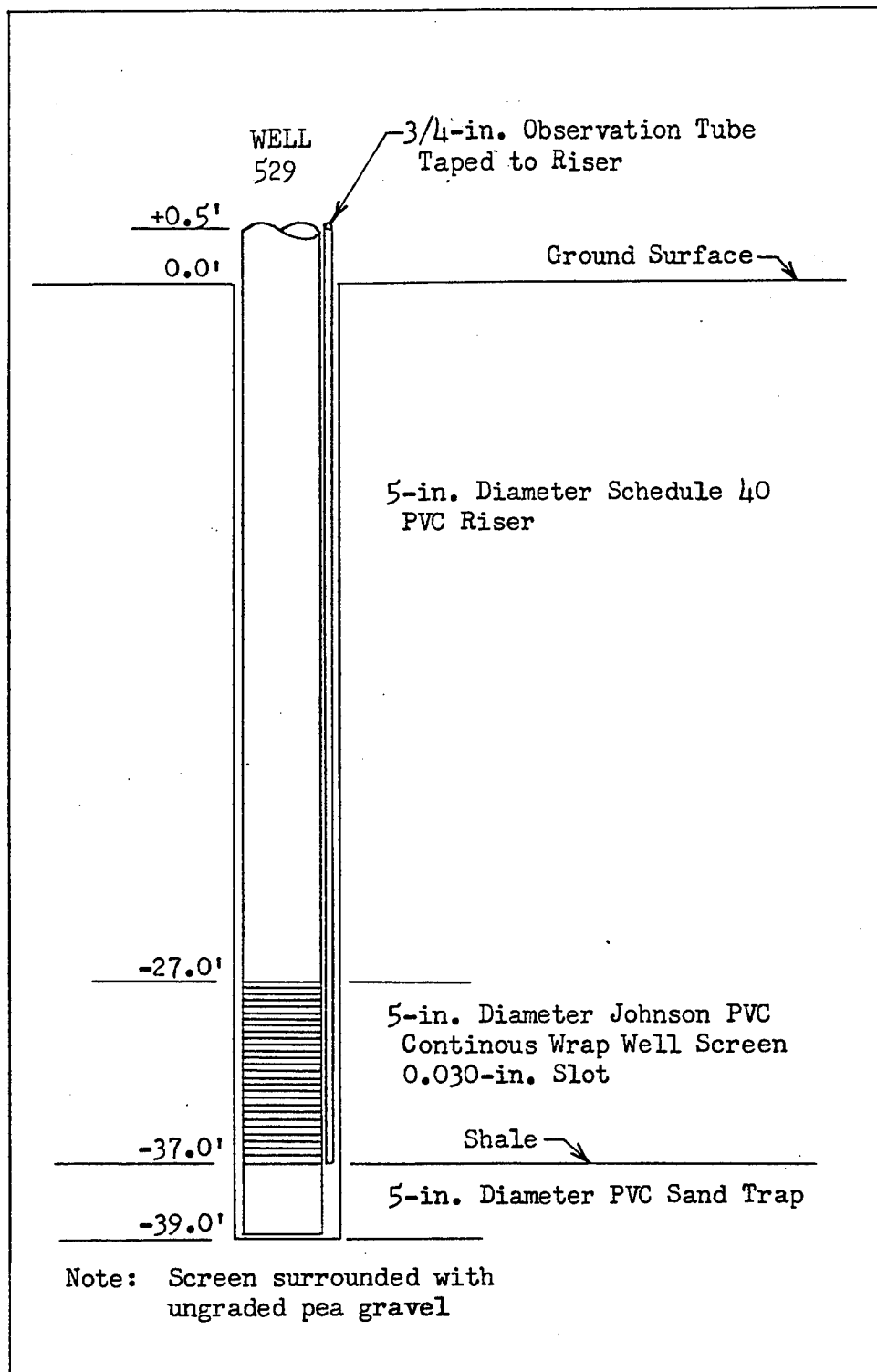


Figure 4. Test Well 529

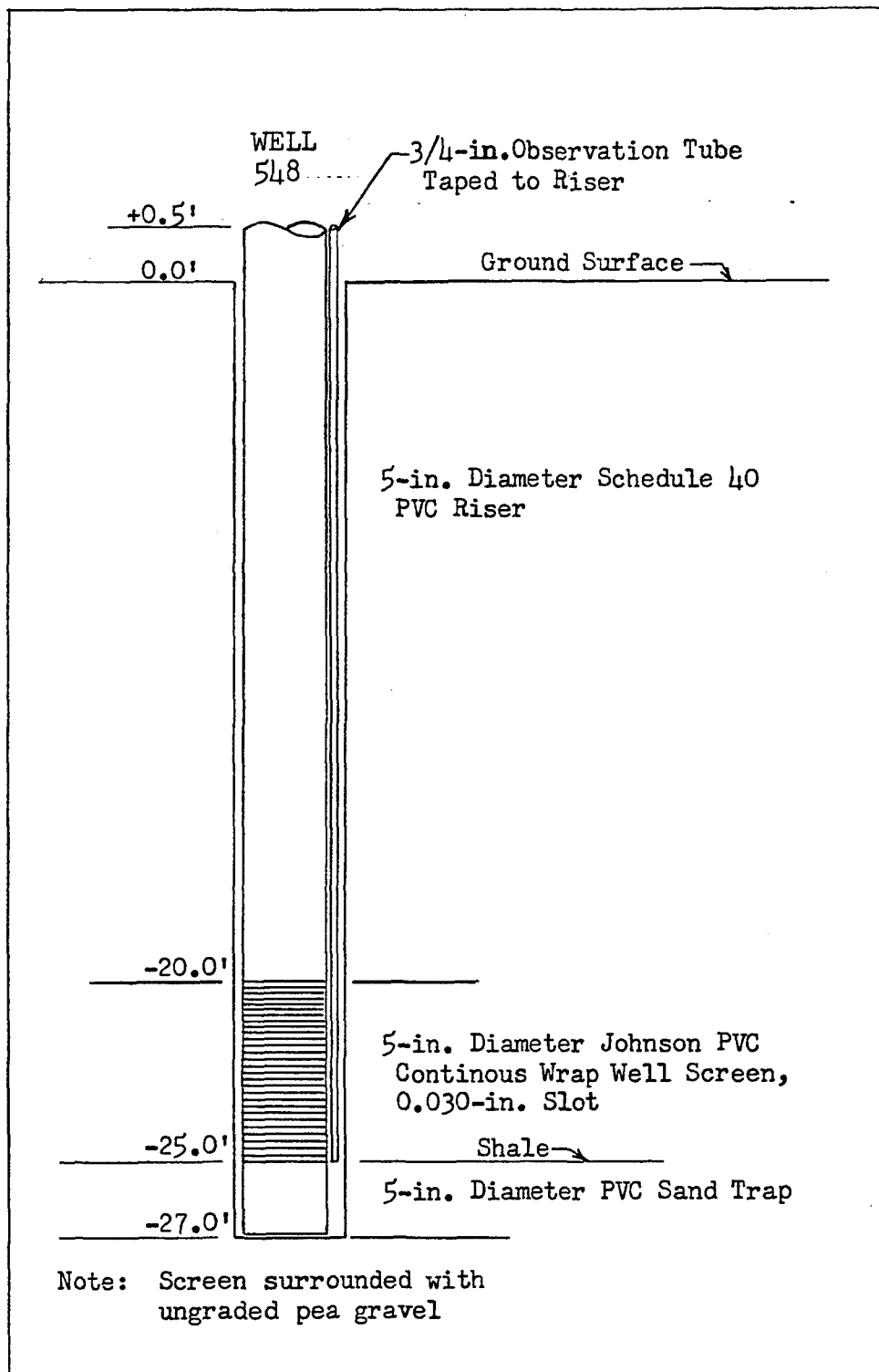


Figure 5. Test Well 548

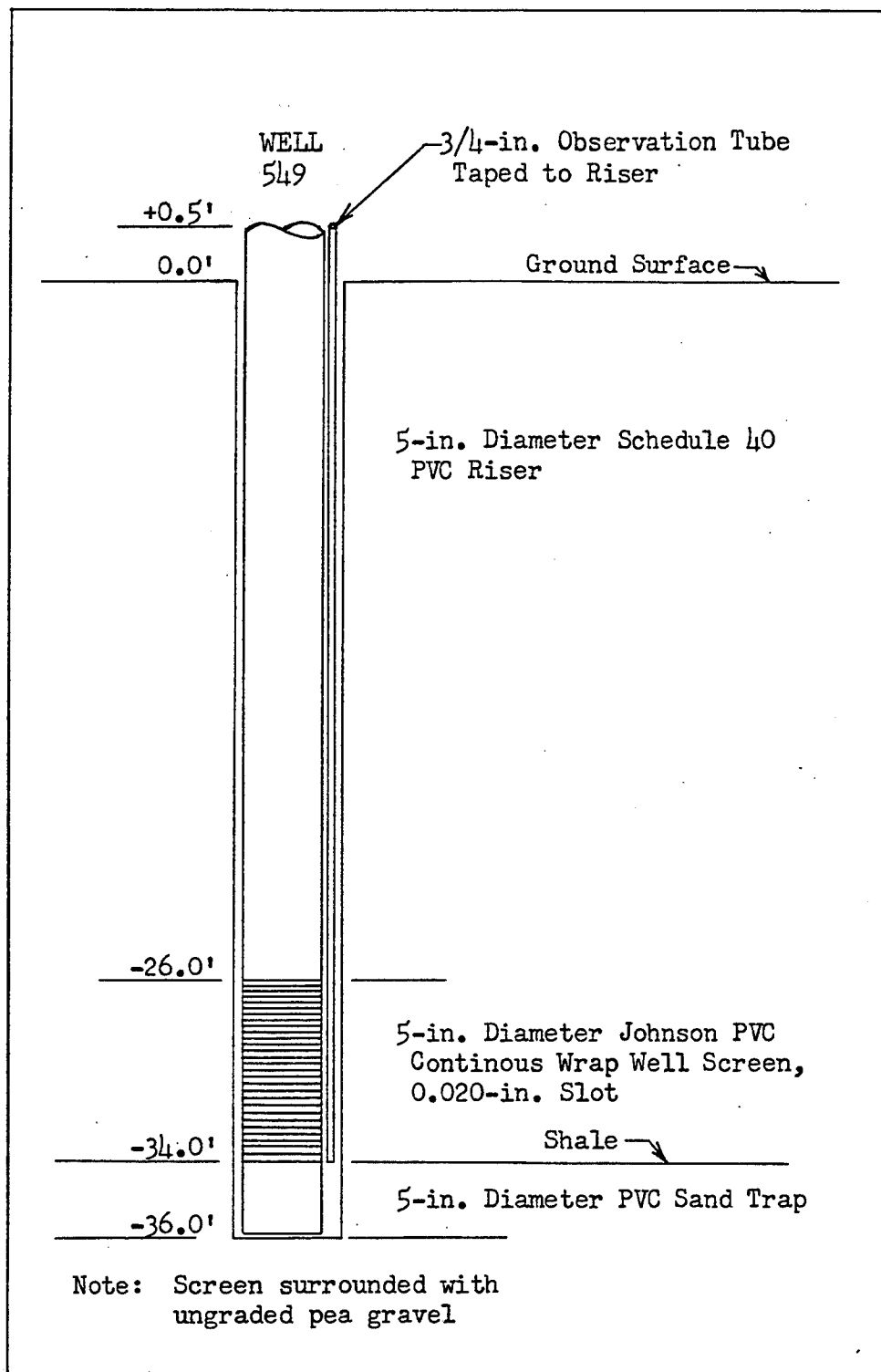


Figure 6. Test Well 549

well sites. Five-inch-diameter schedule 40 PVC pipe was used as the riser pipe between the screen and the ground surface.

4. Each well was developed using a surging block fashioned from a 2.5-in.-diam steel shaft approximately 3 ft long. A disc of 1/2-in.-thick rubber belting, approximately 3/4 in. smaller than the ID of the well, was sandwiched between two 3-in.-diam steel discs at each end of the shaft. The wells were surged by first lowering the surging block to the bottom of the well and then raising it to the top of the screen section using a wire line. The surging block was moved at a rate of 1.5 to 2 ft/sec. For sake of record keeping, 15 round trips of the surging block were considered one cycle. After each cycle, the sand collected in the bottom of the well was sounded. When the collected sand filled the sand trap portion of the well (bottom 2 ft), it was washed out to facilitate development in the lower portion of the screen. Development of the wells continued until there was no appreciable infiltration of sand during one surging cycle.

5. After the test wells were installed and developed by surging, approximately two weeks elapsed before pump testing was planned to commence. During this time a viscous or gelatinous substance formed in the wells. This substance was probably caused by a chemical reaction of the organic drilling fluid residue and the chemicals in the groundwater at RMA. The substance was more prominent in the wells nearer to Basin F. Because of this substance, additional cleaning and development of the wells was necessary before pump testing could be started. This additional development was accomplished by inserting a 3-in.-diam deep well turbine pump into each well and pumping the wells for a minimum of

8 hours. The first few hours of pumping consisted of pumping the well down until the pump sucked air, shutting the pump off and letting the well recover, and then repeating the cycle. The well was then pumped at a steady rate at a maximum drawdown for at least 8 hours or until no sand infiltration could be detected in the effluent.

6. The piezometers or observation wells installed for the pumping tests consisted of a 3-ft-long slotted section of 2-in.-diam PVC pipe set in the aquifer material. Two-inch PVC pipe was used as a riser for these piezometers. All piezometers were installed using a Mobile B-52 truck-mounted drill rig and hollow-stem auger. The auger was advanced to the depth of the bottom of the piezometer, the piezometer screen and riser were inserted through the auger to a predetermined depth and the auger was then pulled out. In most cases, the aquifer material caved around the piezometer screen as soon as the auger was removed. In cases when this did not happen, the piezometer screen was surrounded with ungraded pea gravel from a local source at the RMA. All piezometers were flushed with clear water after installation.

7. Well 345 was pumped using a 3-in.-deep well turbine-type pump driven by a four cylinder Wisconsin engine. Flow from the well was controlled by a 2-in. gate valve and was measured by a 2-in. Badger water meter.

8. Wells 368, 529, 548, and 549 were pumped using a 3-in. Flint and Walling electric motor driven submersible pump. Electric power to operate the pump was provided by one gas engine and one diesel engine driven 15 KW generators. Both generators were operated simultaneously,

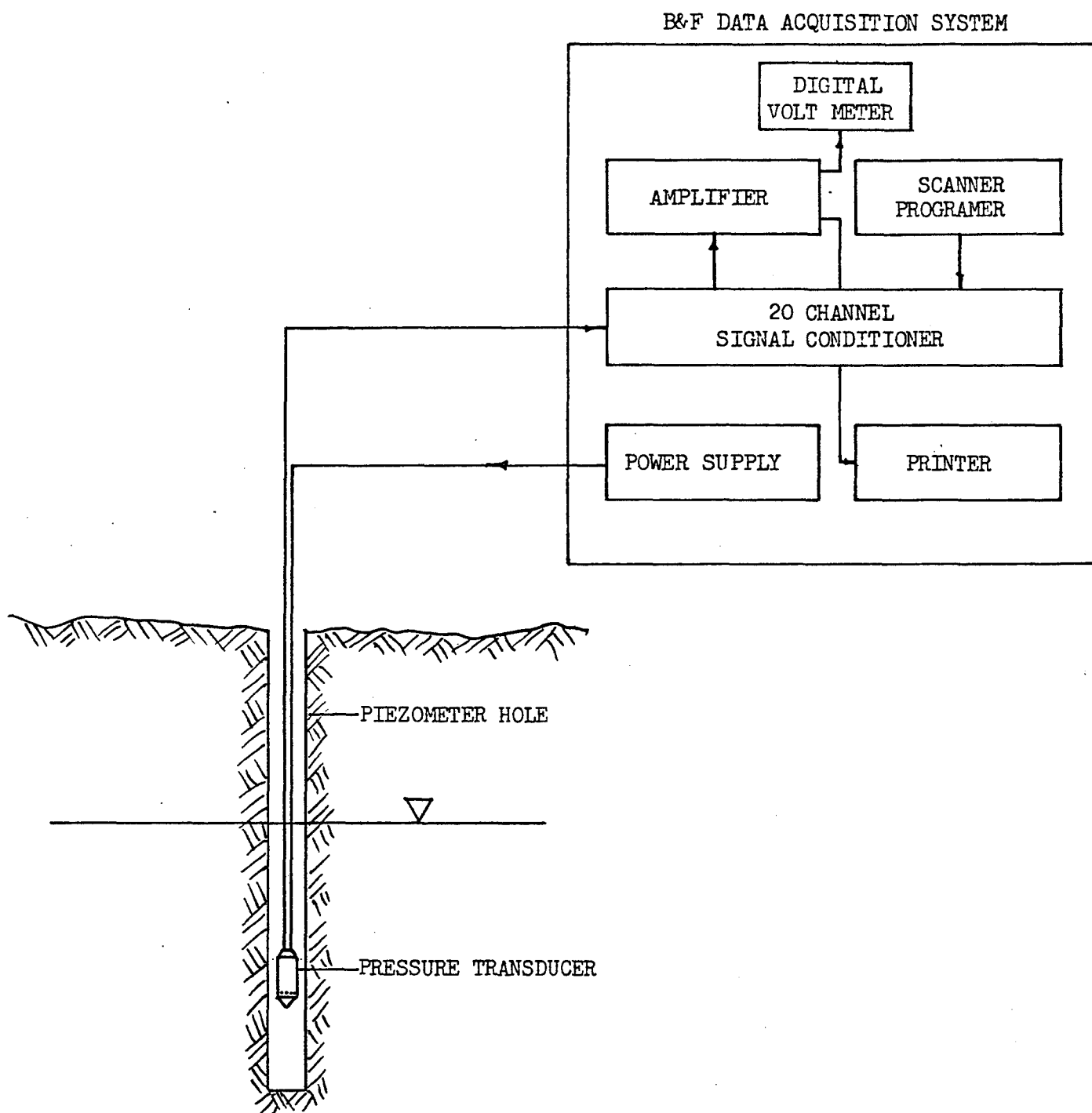
one generator acting as the primary source and the other generator acting as the secondary source. An electrical relay was connected between the two generators to automatically switch to the secondary generator if the primary generator failed. No generator failure occurred during any of the tests.

9. The pumping tests were conducted by the constant discharge method, i.e., the discharge from the well was maintained at a constant rate and the water level in the well and piezometers allowed to continue to drawdown. Minor adjustments of the flow control valve were required to maintain a constant flow because as the drawdown increased, the head on the pump increased causing a slight reduction in flow. These minor adjustments were performed manually for the pump tests on wells 345 and 549 and automatically, as described in forthcoming paragraphs, on wells 368, 529, and 548.

10. At the onset of each pumping test, the drawdowns in the well and the piezometers were measured at rapid intervals. The observation interval was increased with distance from the pumped well and elapsed time from the beginning of the test. The maximum interval between observations in any test was 8 hours. Drawdown in the wells and piezometers is plotted versus log time and presented in following sections. Upon termination of the pumping tests, recovery measurements were made in the well and piezometers. The observations were made at close intervals during the first few minutes of recovery and continued at increasing intervals until the well had virtually recovered. Recovery is plotted versus log time for each well in the respective sections.

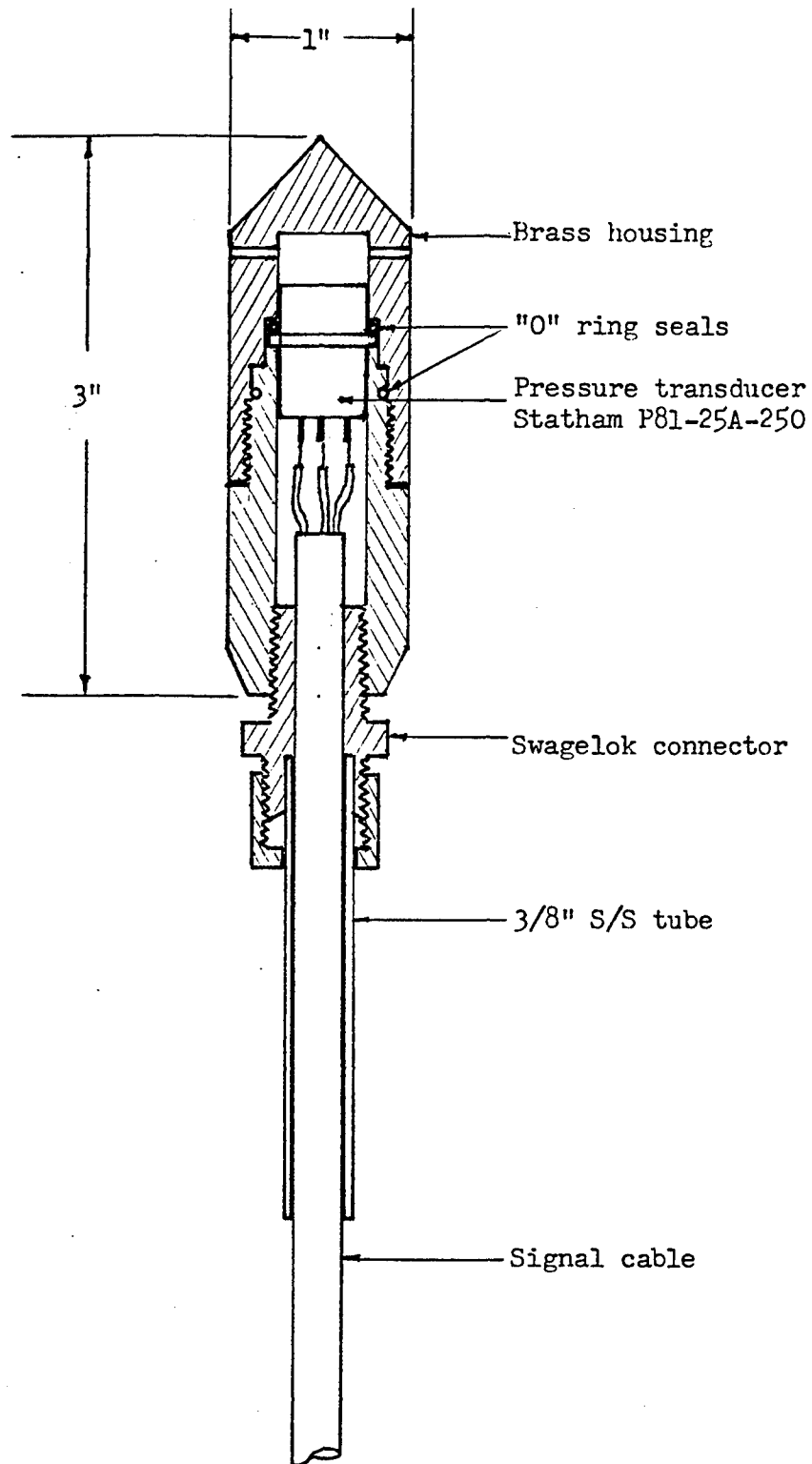
11. All water level measurements during the pump test on well 345 were made manually using a M-scope or a steel tape. Since the water level measurements must be made rapidly at the onset of the pumping test and then again when the pump is stopped and the recovery started, one person with a measuring device was required at the well and each close-in piezometer for the first hour or so of the test. Also, the contaminated water in the area tended to coat the probe of the M-scope causing the meter to deflect full scale and remain pegged. The probe had to be removed from the piezometer and cleaned with fresh water before the next reading. The time consumed could not be tolerated especially at the onset of a test. Using a steel tape to measure water levels is too slow for the short reading intervals required during the early stages of a test. To reduce the manpower need during the startup of a test and to eliminate the unreliability of the M-scope in the contaminated water, an electronic data acquisition system was designed and fabricated by personnel of the Design Investigations Branch, Geotechnical Laboratory, WES, and used for the pump tests on wells 368, 529, 548, and 549.

12. The electronic data acquisition system consisted of strain gage pressure transducers that were set at the bottom of the piezometer riser and connected to a scanner recording unit located near the pump well (see block diagram, Figure 7). The pressure transducers used were Statham P81-25A-120 with a pressure range of 0 to 25 psia. Figure 8 shows a cross section of a pressure transducer housing which was fabricated out of brass to protect the transducer and provide a water-tight connection for the signal cable. The transducers were calibrated to



ELECTRONIC PIEZOMETER MEASUREMENT AND RECORDING SYSTEM

Figure 7



PRESSURE TRANSDUCER AND HOUSING

Figure 8

read directly in feet of water with a sensitivity of 0.01 ft, which alleviated the necessity of converting psi changes to feet of water change for calculations and analysis.

13. The equipment used to scan, display, and record the pressure transducer output was manufactured by B & F Instruments of Cornwells Heights, Pennsylvania. The system primarily consisted of five interacting units; the power supply, signal conditioner, scanner-programmer-amplifier, digital voltmeter (DVM), and printer. The power supply provided regulated excitation voltage to the pressure transducer's strain gage bridge circuit. The signal conditioner incorporated the use of two (B & F SY161) units, which are divided into 10 channels each. Each channel had a zeroing potentiometer, gain control, and scan relay. A calibration circuit was provided on each SY161 unit to allow the pressure transducers to be calibrated in the field. The zeroing potentiometer, as the name implies, allowed the output from the pressure transducer to be zeroed before the start of the test. The zero control also provided a means of rezeroing the transducer after it had been placed in the piezometer riser. The gain control (potentiometer) was used to set or adjust the calibration of the transducers. The scan relays were energized by the programmer unit which connected the transducer circuits to the amplifier and recorder.

14. The scanner-programmer and amplifier were actually two separate systems contained in the same equipment housing. The scanner-programmer provided three modes of operation:

a. Single point - Any channel or data point could be selected and displayed on the DVM indicator. This mode was used while calibrating and zeroing the transducers.

b. Single scan - This mode scans and prints all channels for one cycle and returns to channel 0.

c. Continuous scan - When the programmer was placed in the continuous scan mode the unit continued to scan and print all channels at a rate of 2 channels per second until this scan mode was turned off. The amplifier received the data signals from each channel and amplified the signal to a suitable level to be displayed by the DVM and printer. The DVM had a 4-digit display and read up to 19.99 units. The DVM also provided output required by the data printer. The printer provided a permanent recording of the scanned data on 3-in. paper tape. Each printed line contained both channel identification and transducer data. Electric power for the electronic equipment was provided by the same two generators that supplied power to the pump.

15. The electronic system was designed and fabricated rather hurriedly and was not entirely proof tested before it was sent to the field. Because of this, a few problems were encountered in the field operation of the equipment. The major problem was the fact that the signal cable was temperature sensitive, i.e., the resistance of the individual conductors within the signal cable changed with temperature changes causing the transducer readings to drift and give erroneous pressure readings. Attempts were made to calibrate this change but no correlation could be made between transducer readings and temperature

change. It was first thought that the reason no correlation could be made was because the cable, which was laid out on the ground from the instrument van to the individual piezometers, was, in most cases, partially shaded by the vegetation that covers most of the ground surface. For the next test, the cable was buried in shallow trenches (approximately 8 in. deep) but attempts to correlate temperature change and transducer readings under these conditions were still inconclusive. However, it was learned from these calibration tests that the transducer readings were least affected by temperature changes during mid-morning and then again during the late afternoon. For this reason, the tests were scheduled to start and stop during these periods.

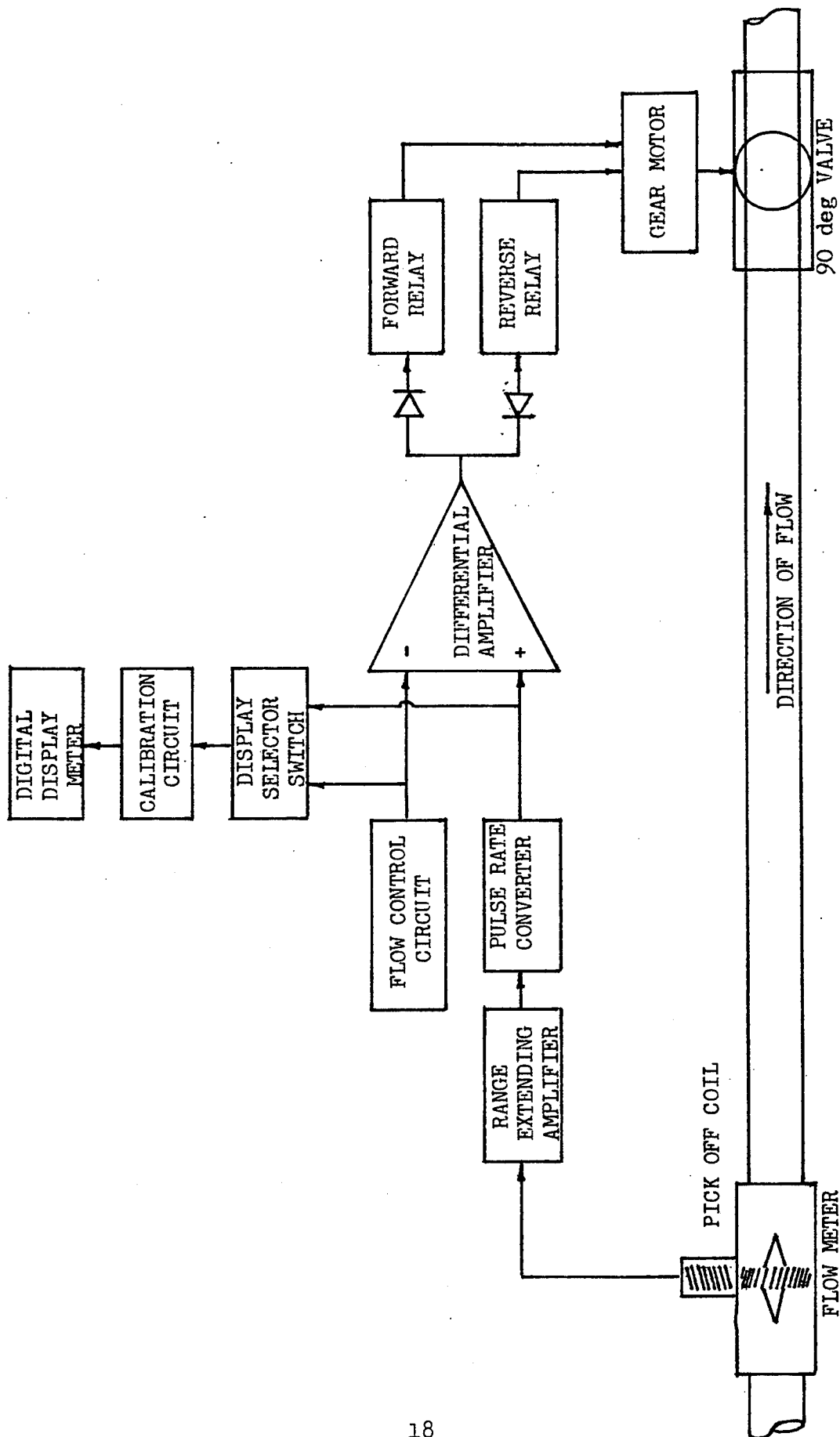
16. Use of the electronic acquisition system was limited on the four wells (368, 529, 548, and 549) to the first two hours of drawdown and then again on the first two hours of the recovery test. This limited use eliminated the requirement for numerous people and obtained rapid successive observations which would not have been possible by making the observations with M-scopes or steel tapes. The piezometers were also read manually during this period (not as rapidly as with the electronic system) primarily as a check on the electronic system. In all tests the electronic readings compared favorably with the manual readings.

17. An electronic system was also designed and fabricated by personnel of the Design Investigations Branch, WES, to measure and control the output flow from the pumped wells. The control system was essentially a closed loop servo system incorporating the use of a turbine flow meter, electronic control circuit, and a motorized valve. To

aid in the operational explanation of the equipment, the system may be separated into five units. Figure 9 is a pictorial block diagram of the various units and their major component parts. The five units of the system are:

a. Flow meter - The flow meter and associated equipment used in this system were manufactured by Flow Technology Inc., Phoenix, Arizona. The flow meter was a 2-1/2-in.-diam in-line turbine unit with an induction pick-off coil. The meter was capable of measuring flows from 5 to 250 gallons per minute (GPM). The turbine rotor was located in the center of the housing, perpendicular to the flow of water. A pick-off coil was mounted on the side of the meter housing in line with the turbine blades. As the turbine rotated, the tips of its blades passed near the pick-off coil causing a change in inductance each time a blade passed the coil. The water flowing through the turbine caused the blades to rotate at a speed directly proportional to the volume of the flow. This rotation in turn caused a pulsating output from the pick-off coil directly proportional to the flow volume. These pulses were fed to the range extending amplifier where they were reshaped and amplified. The amplified signal was then fed into the pulse rate converter (PRC). This unit converted the pulses to an analog voltage directly proportional to the input frequency or pulse rate. This voltage ranged from 0 to 5 volts DC and was directly converted into GPM.

b. Flow control circuit - As with most servo control circuits, this system operated on the principle of matching an unknown signal (in this case an unknown voltage) with a known signal. Matching was accomplished by the use of a calibrated variable voltage divider adjustable from 0 to -5 volts DC.



FLOW CONTROL UNIT

Figure 9

c. Differential amplifier - The differential amplifier received both the positive signal voltage from the flow meter circuit and the negative calibrated voltage from the control circuit. The amplifier summed the two voltages and amplified the difference providing either a positive or negative output voltage of a suitable level to actuate a relay. Two relays were used in the output circuit of the amplifier and are referred to as the forward and reverse relays. Through the use of diodes in series with the relay armatures, either relay could be actuated at a given time depending on the polarity of the amplifier output signal. These relays were used to connect the power to the valve motor causing it to run in the required direction to correct flow rate.

d. Motorized valve - The motorized valve consisted of a 90 deg, 2-in. ball valve connected to a universal motor with a worm gear drive. The motor received its power from the differential amplifier relays through two limit switches. The limit switches restricted the rotation of the valve to 90 deg.

e. Flow display circuit - The flow display consisted of a DVM, display selector switch, and calibration circuit. The DVM used was a common digital panel meter manufactured by Fairchild Electronics. The meter displayed a 1/2-in. numeral size with a range of 0 to 1.999 volts DC. The meter was connected through the display selector switch to either the flow meter output, the control circuit output, or the sum of both. In order for the digital display to read directly in GPM's, a shunt calibration circuit was built into the meter circuit. This circuit enabled the operator to adjust the meter input voltage from a fixed

voltage source corresponding to a known flow rate to read a given GPM. For example, if a flow rate of 100 GPM produced an output voltage from the pulse rate converter of 2.000 VDC, the display meter would be adjusted to read 100.0 mili volts.

18. The variable voltage divider was adjusted to produce the desired flow after the display meter had been calibrated and the meter control switch placed in the control circuit position. When the motorized valve was in the fully closed position, a no-flow or zero voltage would be present at the output of the PRC unit. The differential amplifier would produce a negative output causing the motor valve to begin opening. As the flow of water through the flow meter increased, the positive voltage at the output of the PRC would also increase. When this positive voltage equaled the negative voltage from the control circuit, the output from the differential amplifier would be zero and the valve motor would stop. If the flow rate increased above the set point on the control circuit, the differential amplifier would produce a positive output voltage reversing the valve motor restricting the flow through the valve until once again equilibrium was attained. The display selector switch could be placed in the flow meter position to observe the flow rate and fluctuations. The control circuit would adjust to flow variations of ± 0.5 GPM's.

19. Well 549 was pumped at a flow rate of 5 GPM which produced problems with the flow meter and automatic flow control valve. The 5 GPM flow was too small for the 2-1/2-in.-diam flow meter to monitor. Although the meter was designed to measure in this range, the flow rate

display fluctuated intolerably. This fluctuation caused the automatic flow control valve to continually adjust in a futile attempt to maintain a steady flow. This continual adjustment caused an actual variation in flow. All attempts to stop the fluctuation in the flow meter read out failed so this system was abandoned. Flow from well 549 was then measured with a 3/4-in. Rockwell water meter and controlled manually with a 3/4-in. globe valve.

20. A flow rate was determined for each test when the wells were subjected to eight hours of continuous pumping during their development. The flow rate was chosen to allow the maximum drawdown but yet maintain the water surface above the pump suction after approximately three days of pumping. Prior to the start of the pump test (at least 24 hours), the pump was operated and the flow control valve set at the predetermined rate, eliminating the need to manipulate the valve during the first portion of the pump test which would have produced unsteady flow during this period.

21. All five pumping tests were analyzed using the Theis, Jacob, Chow, and Theis Recovery methods for nonequilibrium flow. These methods are based on the following assumptions:

- a. The aquifer is homogeneous, isotropic, and of uniform thickness over the area influenced by the pumping test.
- b. The aquifer has a seemingly infinite extent.
- c. Prior to pumping, the piezometric surface and/or phreatic surface is nearly horizontal over the area influenced by the pumping tests.

d. The aquifer is pumped at a constant discharge rate.

In most cases, these assumptions cannot be satisfied (especially a and b), however, slight deviations are not prohibitive to the methods. The following is a description of each of the four methods used for analysis.

22. Theis. Transmissibility, which is the aquifer permeability multiplied by the aquifer thickness, is determined using the Theis method by the formula

$$T = \frac{115Q W(u)}{S}$$

where: T = aquifer transmissibility in gallons per day per foot of aquifer width

Q = pumping rate in gallons per minute

W(u) = a well function determined from a type curve

S = drawdown, in feet, at observation piezometer

A drawdown versus $\log t/r^2$ (t is time in minutes, r is the distance, in feet, of the piezometer from the pumped well) curve is superimposed on the Theis type curve so that the plotted points fall on or fit some portion of the type curve. In finding the position of best fit, the axis of both curves must be kept parallel. Once a good matching position is found, a match point is selected. From this match point, the value of W(u) can be selected corresponding to the value of S (drawdown). These two values are then used in the above formula to solve for T.

23. Jacob. The Jacob method is based on the assumption that the plot of drawdown versus the logarithm of time forms a straight line which is normally true for the latter portions of a test and if the

previously mentioned assumptions are met. Determination of transmissibility can be made by the Jacob method using the following formula:

$$T = \frac{264Q}{\Delta S}$$

where: T = aquifer transmissibility in gallons per day per foot of aquifer width

Q = pumping rate in gallons per minute

ΔS = drawdown difference, in feet, per log cycle of time on the drawdown versus log of time plot

The transmissibility of the aquifer can also be computed from the Jacob method using the drawdown versus log of distance from pumped well plot. The only difference in the formula is that the constant changes from 264 to 528. Conditions placed on the Jacob method require that the following criteria be met:

$$\frac{1.87 r^2 S}{Tt} < 0.01$$

and

$$S = \frac{0.3T t_o}{r^2}$$

where: r = distance, in feet, from the pumped well to the observation piezometer

S = coefficient of storage, dimensionless

T = transmissibility in gallons per day per foot of aquifer width

t = time since pumping started, in days

t_o = intercept of the straight line (drawdown versus log of time plot) at zero drawdown, in days

The criteria were met in all calculations using this method for the five pumping tests conducted.

24. Chow. This method has the advantages of avoiding curve fitting and is unrestricted in its application. The drawdown versus log time data are plotted in the same manner as with the Jacob method. On the plotted curve, an arbitrary point is chosen. A tangent to the curve at this point is drawn and the drawdown difference (ΔS) in feet per log cycle of time is determined from this tangent line. A function $F(u)$ can then be determined using the formula

$$F(u) = \frac{S}{\Delta S}$$

where: S = drawdown at the chosen point, in feet

ΔS = drawdown difference, in feet, per log cycle of time on the tangent line

A well function $W(u)$ can then be determined from a standard plot of $W(u)$ versus $F(u)$ calculated by Chow. The value of $W(u)$ can then be used in the following formula

$$T = \frac{115Q W(u)}{S}$$

where: T = aquifer transmissibility in gallons per day per foot of aquifer width

Q = pumping rate in gallons per minute

$W(u)$ = well function determined from a standard plot by Chow

S = drawdown, in feet, at the arbitrarily chosen point on the drawdown versus log of time plot

25. Theis Recovery. After pumping has stopped, the water level will recover to its original level. The water level rise is measured as

the residual drawdown, which is the difference between the original water level prior to pumping and the water level measured at a certain time after the pumping stopped. The residual drawdown is plotted versus the log of ratio t/t' , where t is the total elapsed time since the pumping started and t' is the total elapsed time since the pumping stopped. Transmissibility can be calculated from this plot using the following formula

$$T = \frac{264Q}{\Delta h}$$

where: T = aquifer transmissibility in gallons per day per foot of aquifer width

Q = pumping rate in gallons per minute

Δh = residual drawdown difference, in feet, per log cycle of t/t' on the residual drawdown versus log t/t' curve

26. All of the above methods solve for T , the transmissibility of the aquifer. Permeability can then be determined by the following formula

$$K = \frac{T}{D}$$

where: K = aquifer permeability in gallons per day per square foot of aquifer

T = aquifer transmissibility in gallons per day per foot of aquifer width

D = aquifer thickness in feet

The dimensions of the above permeability can be changed to ft/min by dividing by 10,770.

27. The aquifer pumped in all five tests was not at all uniform and the aquifer thickness varied considerably. Because of this, it was decided to use all four methods to analyze the tests rather than to choose one method that was felt best fit the situation. Because the aquifer did not meet the assumptions upon which the formulas are based, plus the fact that the formulas themselves are not based on the same assumptions, the use of four methods causes a range of transmissibilities and permeabilities for each piezometer analyzed. All four methods of analysis were primarily developed for a confined aquifer or artesian flow but can be used in an unconfined aquifer or gravity flow situation, when the drawdown is small with respect to the aquifer thickness. This was the case in all the gravity flow situations for the five pumping tests conducted.

28. In all five pumping tests, the 5, 10, 50, and 100-ft piezometers were analyzed using the previously described methods. The pumped well was analyzed using the Theis Recovery method only. In all five tests, the drawdown in the 500 and 1000-ft piezometers was not large enough to give a meaningful drawdown versus log of time plot; therefore, they were not analyzed individually, but the drawdown in these piezometers was used in the drawdown versus log of distance from pumped well plots. Also, the recovery was not monitored in any of the 500 and 1000-ft piezometers.

29. Figure 10 shows the piezometer locations for the pump test at well 345. Figures 11 through 21 are the drawdown and residual drawdown (recovery) versus log time plots for the well and all the piezometers.

Figure 22 is the final drawdown versus log of distance from pumped well plot for the well 345 pumping test. Table 1 is a summary of the transmissibilities and permeabilities calculated for the 5, 10, 50 and 100-ft piezometers on the two piezometer lines plus an average transmissibility and permeability along the two lines.

30. The aquifer thickness used in the calculations was determined by taking an average of the aquifer thickness that was measured at the piezometer borings that were logged and interpolating to determine aquifer thickness at piezometer locations that were not logged. According to the available piezometer boring logs for this site, the water table was in the aquifer in some areas and above the aquifer in some areas which indicates a combination of gravity flow and artesian flow. The methods of analysis for both types of flow are the same as long as the drawdown is small in relation to the aquifer thickness in a gravity flow situation. This criteria was met in this case.

31. Inspection of Table 1 reveals that the aquifer transmissibility at each of the piezometer locations compare fairly well, but the permeability appears to increase out to the 100-ft piezometers. Inspection of the boring logs indicates the aquifer material is coarser at the 100-ft piezometers, which could account for the higher permeability.

32. Figure 23 shows the piezometer locations for the pump test on well 368. Figures 24 through 34 are the drawdown and residual drawdown (recovery) versus log time plots for the well and all the piezometers. Figure 35 is the final drawdown versus log of distance from pumped well plot for the well 368 pumping test. Table 2 is a summary of the transmissibilities and permeabilities calculated for the 5, 10, 50, and 100-

ft piezometers on the two piezometer lines plus an average transmissibility and permeability along the two lines.

33. The drawdown versus log time plots show that the slope of the curve steepens with increasing time which indicates the expanding cone of depression encountered a less permeable zone or boundary condition. The four methods used to analyze this test are based on the assumption that the aquifer is homogenous which is not valid in this case. Calculations were made using both distinct slopes on each curve. The lower values of transmissibility were calculated from the steeper portion of the curve. The Jacob, Chow, and Theis Recovery methods depend primarily on the slope of the drawdown versus time curve. The Theis method is more of an average type calculation for the entire length of the pumping test. In all cases, the results of the Jacob and Chow methods on each of the two distinct slopes compared favorably, and the Theis and Theis Recovery methods results fell just a little higher than the average of the Jacob and Chow results on the two slopes. Johnson¹ says that the aquifer coefficients must be calculated from the early portion of the test when boundary conditions change during the test. In all the plots, the slope changed at approximately 250 minutes and stayed the same until the pump was stopped at 3200 minutes. It is felt that this is more indicative of the aquifer characteristics especially during long-range pumping. The large range of transmissibilities and permeabilities is the result of calculating these parameters using the two distinct curve slopes.

¹ Ground Water and Wells, Edward E. Johnson, Inc., 1966.

34. The aquifer thickness used in the calculations was taken as the thickness of the saturated portion of the aquifer as determined from the piezometer boring logs. In this test, all piezometer borings were logged. The aquifer thickness used to calculate the average permeability along the two piezometer lines was determined by taking an average of the saturated aquifer thickness along the line. This test was conducted in a water table aquifer, i.e., the top of the water table was within the aquifer.

35. Figure 36 shows the piezometer locations for the pump test at well 529. Figures 37 through 47 are the drawdown and residual drawdown (recovery) versus log time plots for the well and all the piezometers. Figure 48 is the final drawdown versus log of distance from the pumped well plot for the well 529 pumping test. Table 3 is a summary of the transmissibilities and permeabilities calculated for the 5, 10, 50, and 100-ft piezometers on the two piezometer lines plus an average transmissibility and permeability along the two lines.

36. The drawdown versus log time plots for this test also show a steepening of the curve with increasing time indicating a change in boundary condition. Calculations for this test were handled in the same fashion as for well 368, i.e., both slopes of the curve were analyzed, the higher results obtained from the flatter portion of the curve. In this case, the transmissibility calculated by the Jacob and Chow method on the flat portion of the curve were extremely high and unreasonable, therefore, the Jacob and Chow methods were only used on the latter portion of the curve where the results compared favorably with the Theis and Theis Recovery methods.

37. This test was conducted in a water table aquifer, i.e., the water table was within the aquifer. The aquifer thickness used in the calculations was taken as the thickness of the saturated portion of aquifer at the logged piezometer boring locations. The aquifer thickness was interpolated between logged piezometer borings to determine the aquifer thickness at piezometer locations that were not logged. The aquifer thickness used to calculate the average permeability along the two piezometer lines was determined by taking an average of the saturated aquifer thickness along the line.

38. Figure 49 shows the piezometer locations for the pump test on well 548. Figures 50 through 65 are the drawdown and residual drawdown (recovery) versus log time plots for the well and all piezometers. Figure 66 is the final drawdown versus log of distance from pumped well plot for the well 548 pumping test. Table 4 is a summary of the transmissibilities and permeabilities calculated for the 5, 10, 50, and 100-ft piezometers on the three piezometer lines plus an average transmissibility and permeability along the three lines.

39. The range of transmissibilities calculated for the individual piezometers agree quite favorably and the permeability appears to increase at increasing distances from the pumped well. This increase is evident both in the individual piezometer analysis and in the drawdown versus log of distance plots especially in the East and Southwest directions. For this reason, the average permeability along the three piezometer lines was calculated for the two distinct curve slopes, one from 0-50 ft and the other from 50-1000 ft.

40. According to the available piezometer boring logs for this site, the water table was in the aquifer in some areas and above the aquifer in some areas. All data was analyzed using the same methods because in all cases, the drawdown was small compared to the aquifer thickness. Aquifer thickness was calculated as an average thickness determined from the piezometer borings that were logged.

41. Figure 67 shows the piezometer locations for the pump test at well 549. Figures 68 through 78 are the drawdown and residual drawdown (recovery) versus log time plots for the well and all the piezometers. Figure 79 is the final drawdown versus log of distance from the pumped well plot for the well 549 pumping test. Table 5 is a summary of the transmissibilities and permeabilities calculated for the 5, 10, 50, and 100-ft piezometers on the two piezometer lines plus an average transmissibility and permeability along the two lines.

42. Examination of Table 5 reveals that the calculated permeabilities for the 50 and 100-ft piezometers are considerably higher than those for the 5 and 10-ft piezometers. Also, the plots of drawdown versus log time for the 5 and 10-ft piezometers show a distinct slope change (flattening) at approximately 40 minutes. This flattening of the curve means that the expanding cone of depression probably encountered a more permeable material. This interpretation agrees with the individual piezometer calculations and also with the drawdown versus log of distance from pumped well curve, which also has two distinct slopes. For this reason, an average permeability was calculated for each of the two slopes on the drawdown versus log of distance plot.

43. According to the available piezometer logs for this site, the water table was above the aquifer in most areas but was in the aquifer in some areas. All data were analyzed using the same methods because the drawdown was small compared to the aquifer thickness. Aquifer thickness at this site was calculated as an average thickness determined from the piezometer borings that were logged.

Table 1: Well 345
(Pumping rate - 35 GPM)

<u>Piezometer</u>	<u>Analysis Method</u>	<u>Transmissibility (gpd/ft)</u>	<u>Aquifer Thickness (ft)</u>	<u>Permeability (gpd/ft²)</u>
5 E	Theis, Jacob, Chow and Theis Recovery	31,200-33,000	13.7	2,280-2,400
10 E	Theis, Jacob, Chow and Theis Recovery	33,300-38,500	13.3	2,500-2,890
50 E	Theis, Jacob, Chow and Theis Recovery	32,420-45,070	10.4	3,120-4,330
100 E	Theis, Jacob, Chow and Theis Recovery	26,570-42,000	6.7	3,960-6,270
5 S	Theis, Jacob, Chow and Theis Recovery	34,200-44,300	13.8	2,480-3,210
10 S	Theis, Jacob, Chow and Theis Recovery	34,540-35,400	13.7	2,520-2,580
50 S	Theis, Jacob, Chow and Theis Recovery	32,421-50,100	12.4	2,610-4,040
100 S	Theis, Jacob, Chow and Theis Recovery	34,870-42,400	10.8	3,230-3,930
Well	Theis Recovery	33,000	14.0	2,357
East line	Jacob (Drawdown vs log distance)	39,320	9.6	4,100
South line	Jacob (Drawdown vs log distance)	35,540	10.3	3,450

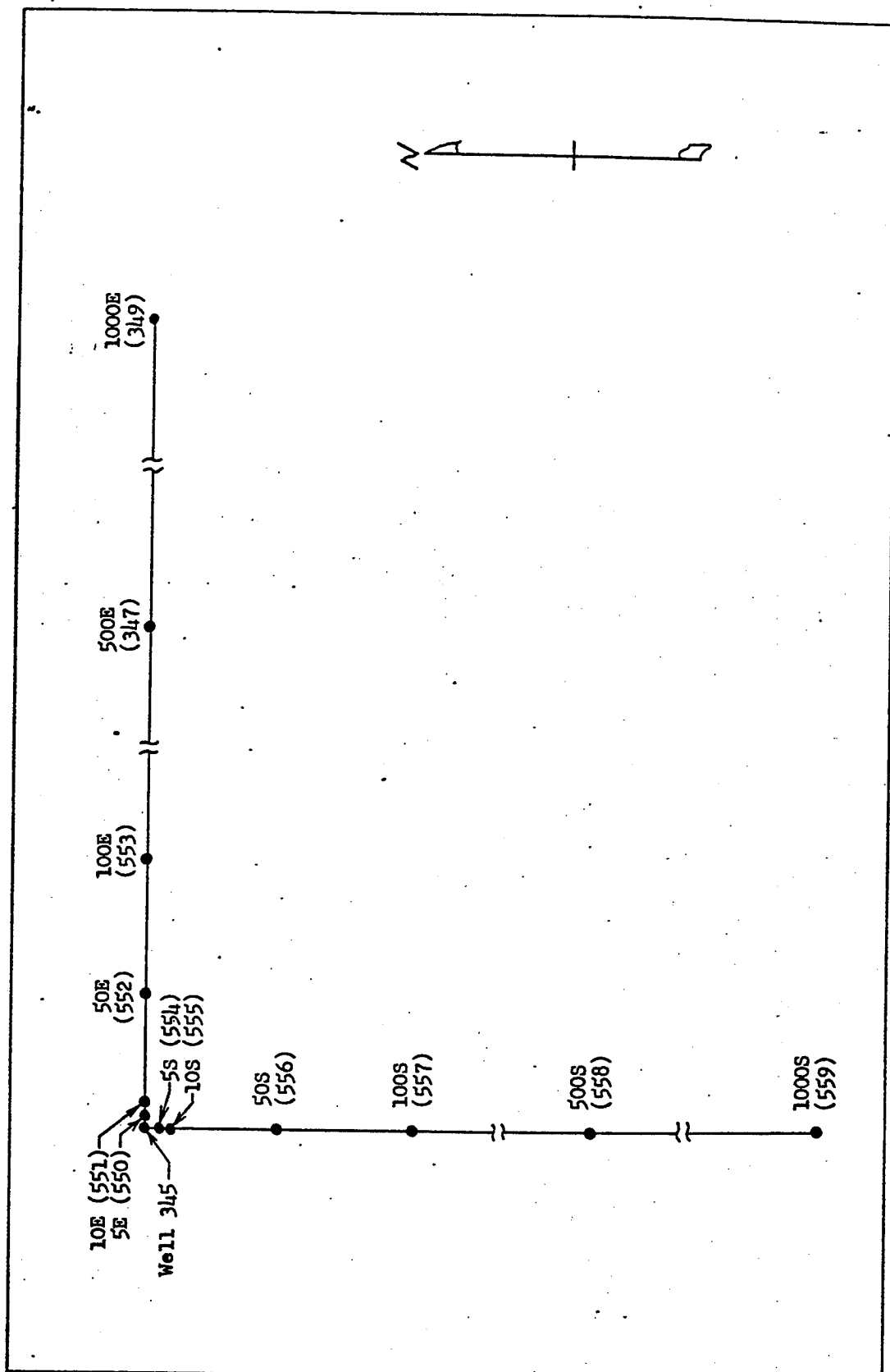


Figure 10. Piezometer layout for Test Well 345

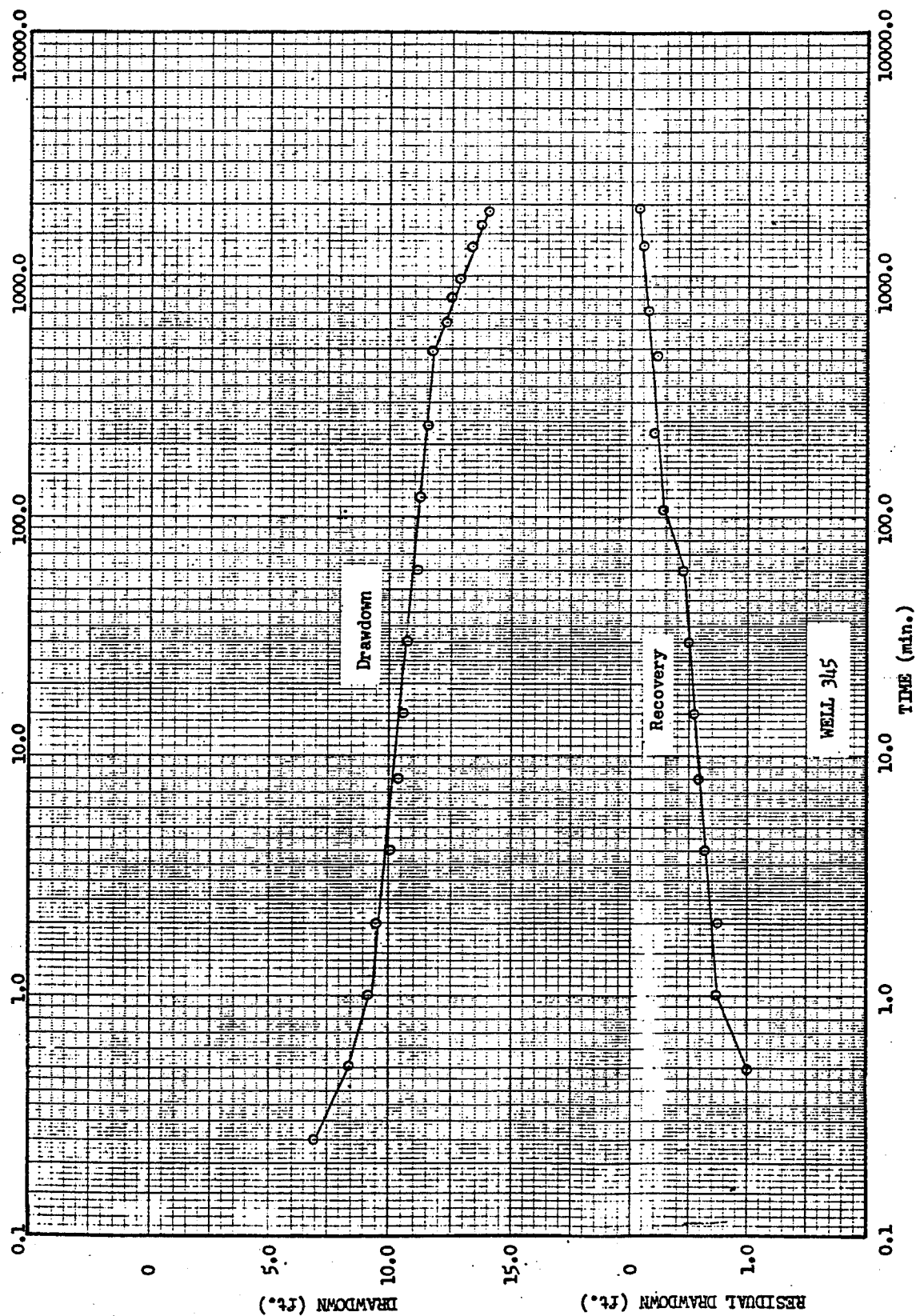


Figure 11. Drawdown and recovery versus time, Well 345

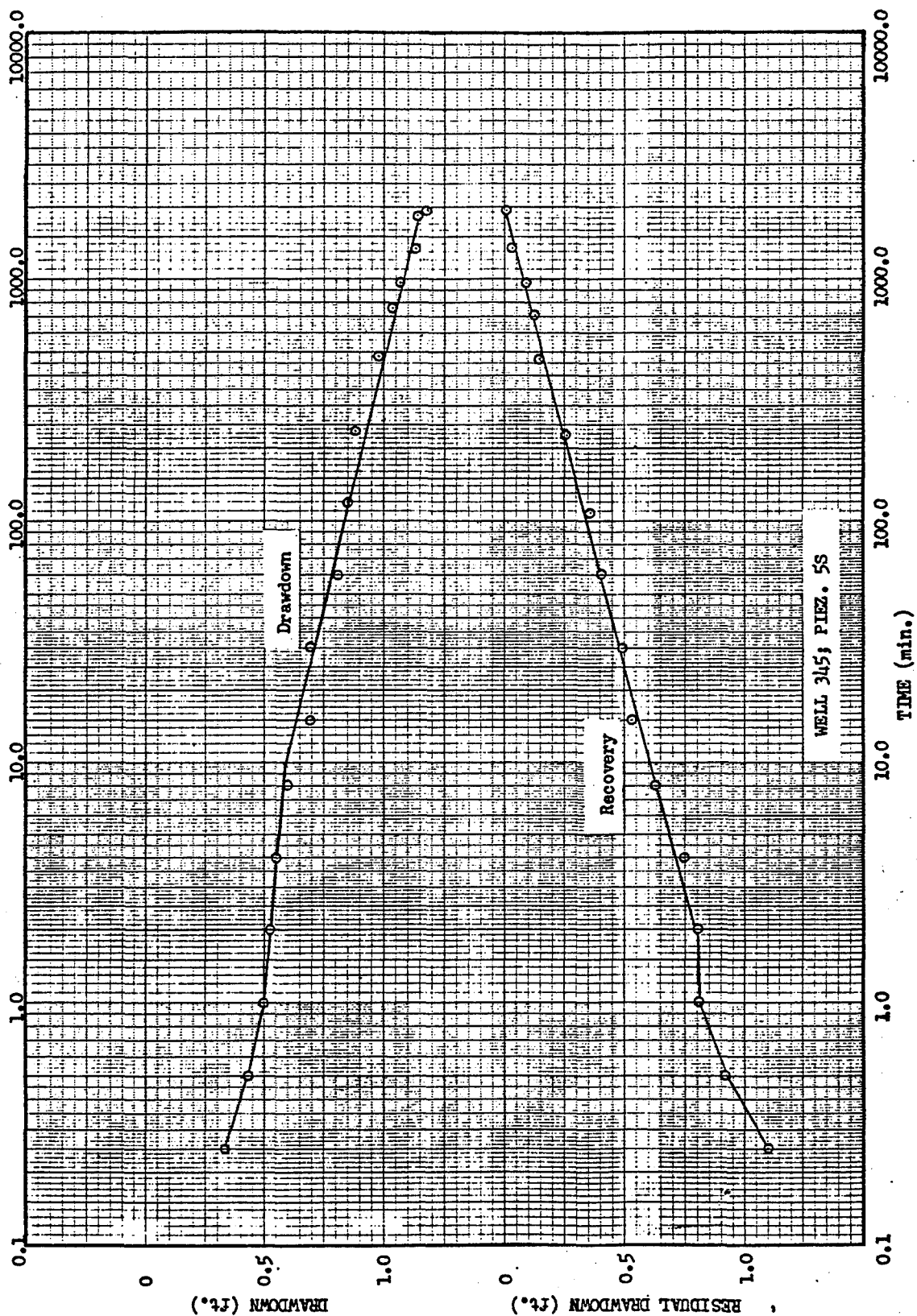


Figure 12. Drawdown and recovery versus time, Well 345; Piezometer 5S

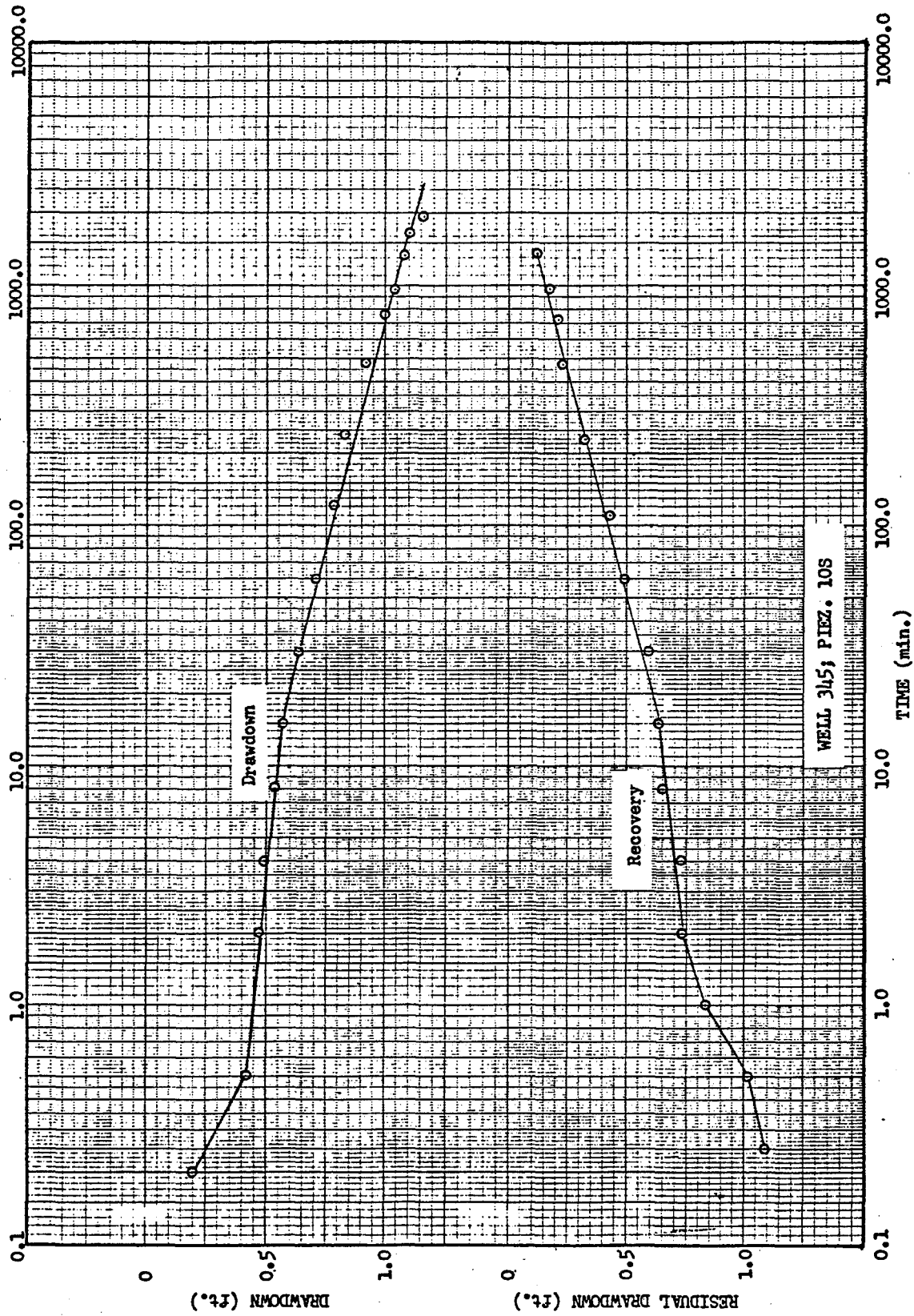


Figure 13. Drawdown and recovery versus time, Well 345; Piezometer 10S

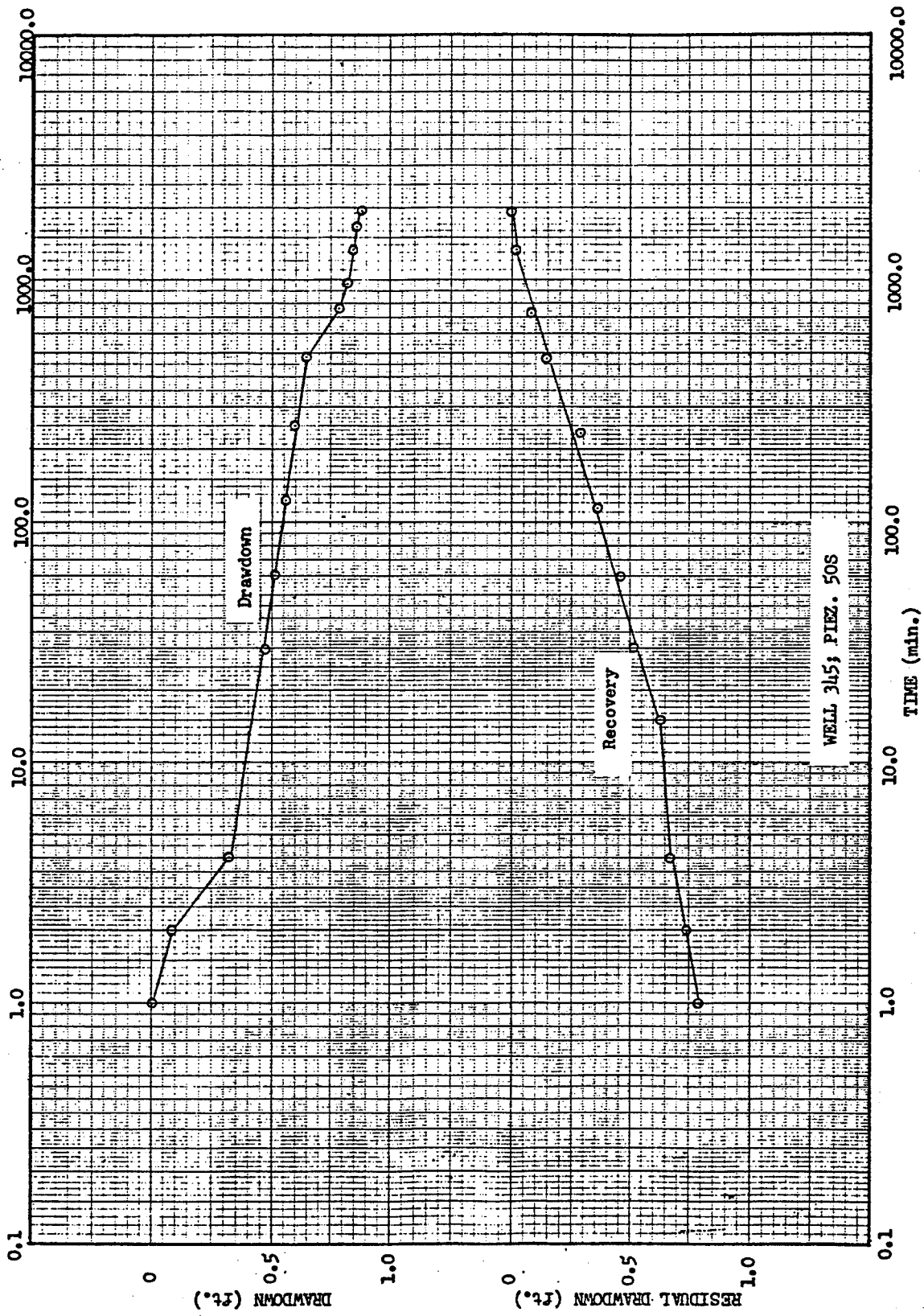


Figure 14. Drawdown and recovery versus time, Well 345; Piezometer 50S

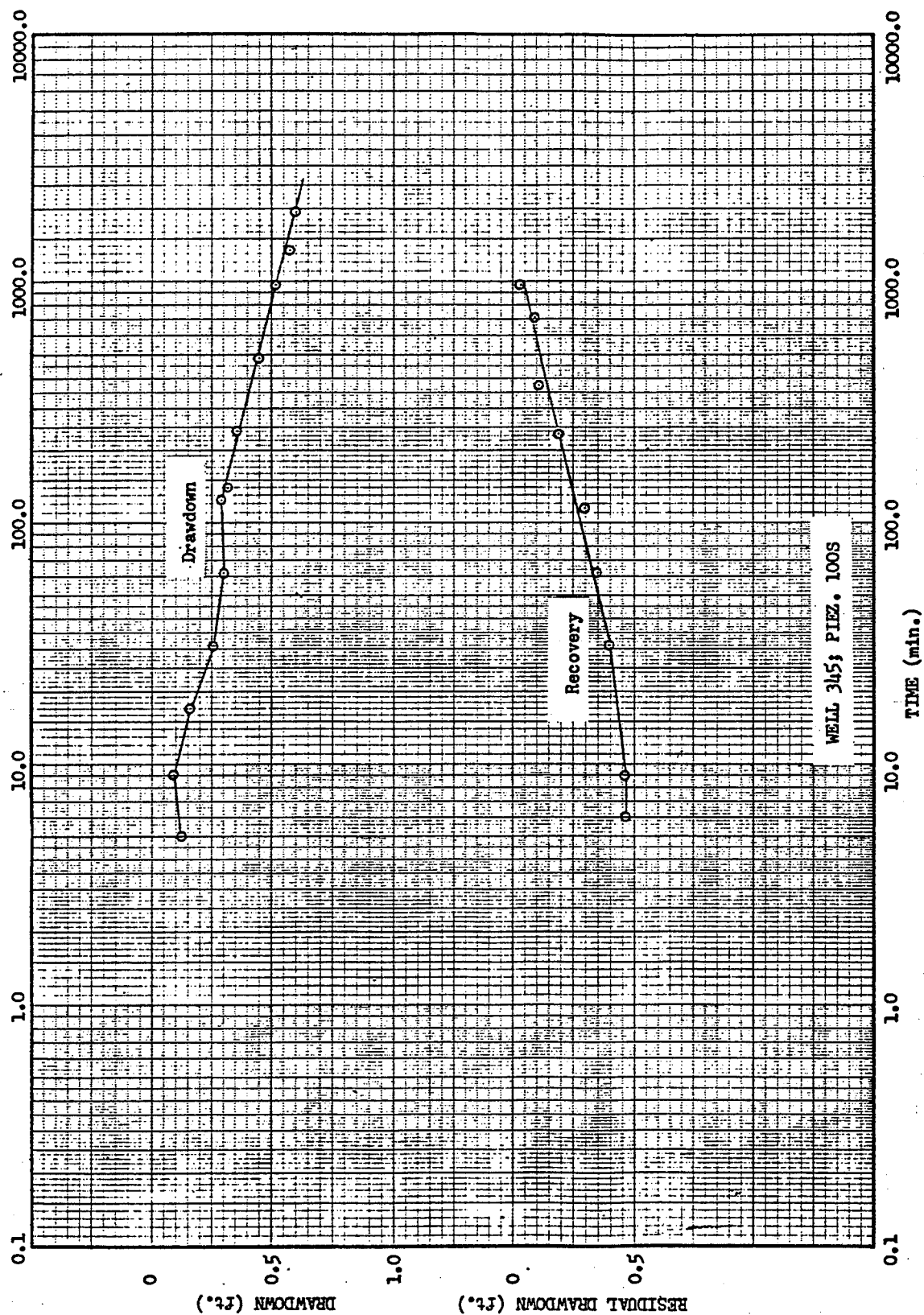


Figure 15. Drawdown and recovery versus time, Well 345; Piezometer 100S

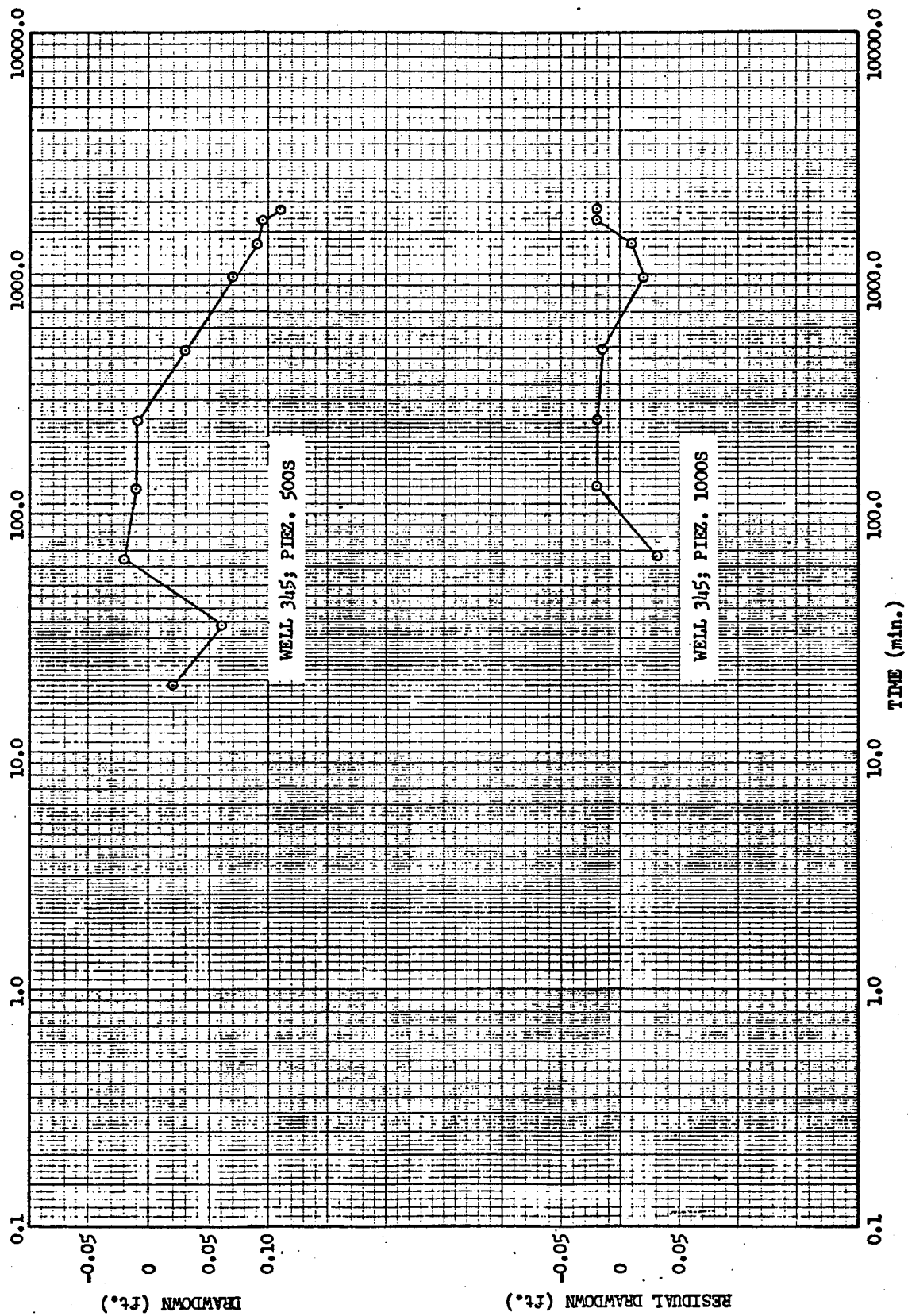


Figure 16. Drawdown versus time, Well 345; Piezometers 500S and 1000S

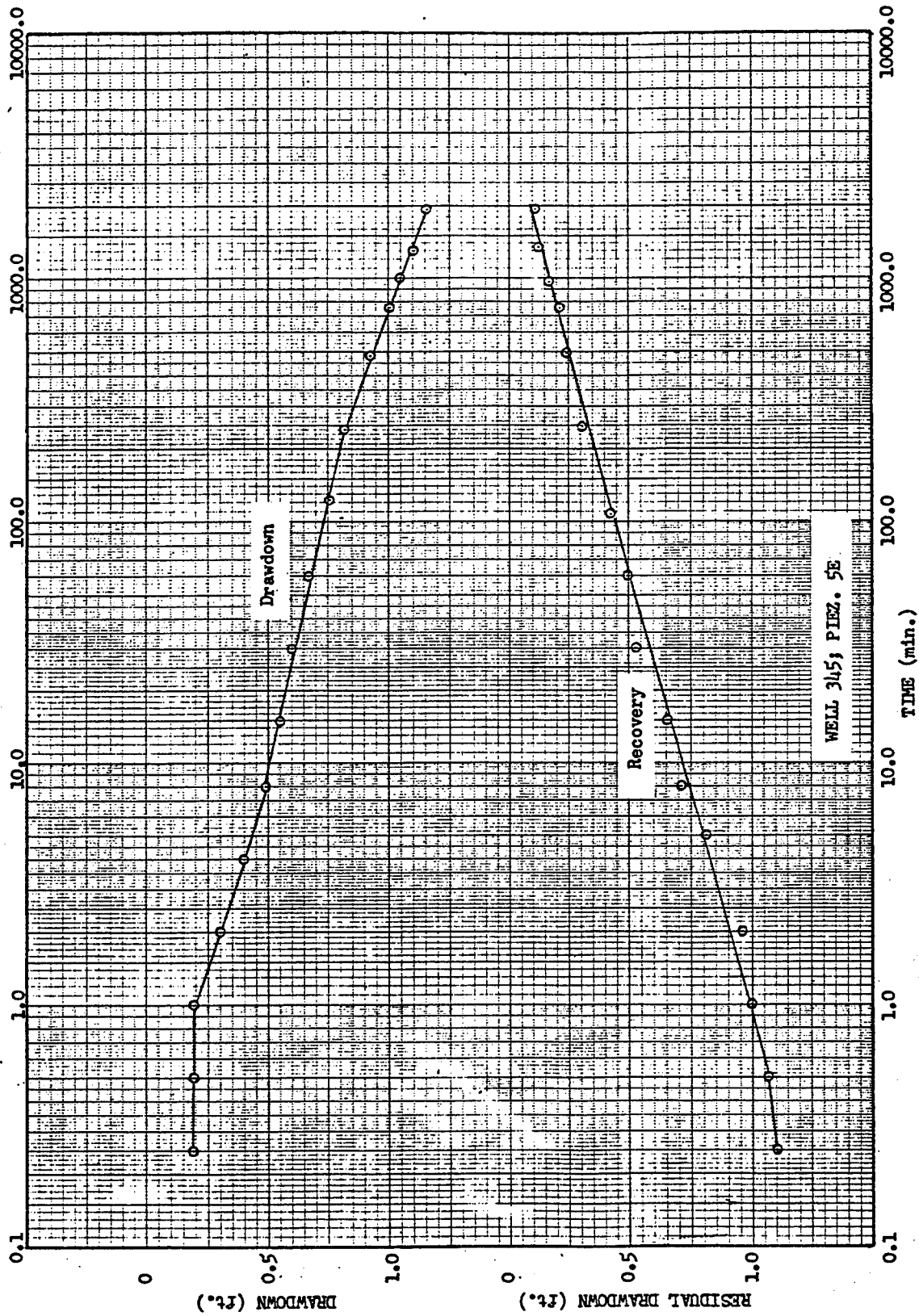


Figure 17. Drawdown and recovery versus time, Well 345; Piezometer 5E

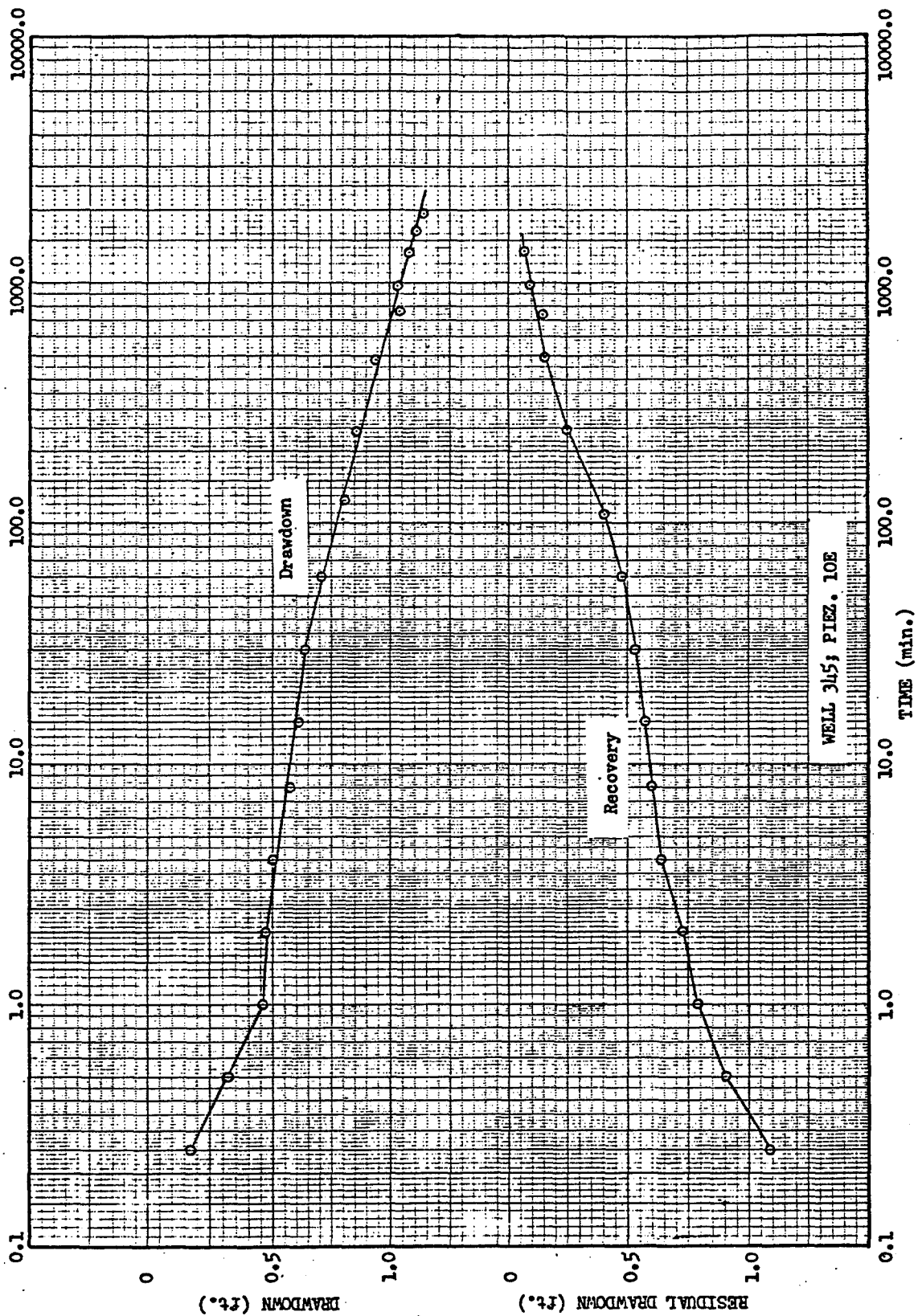


Figure 18. Drawdown and recovery versus time, Well 345; Piezometer 10E

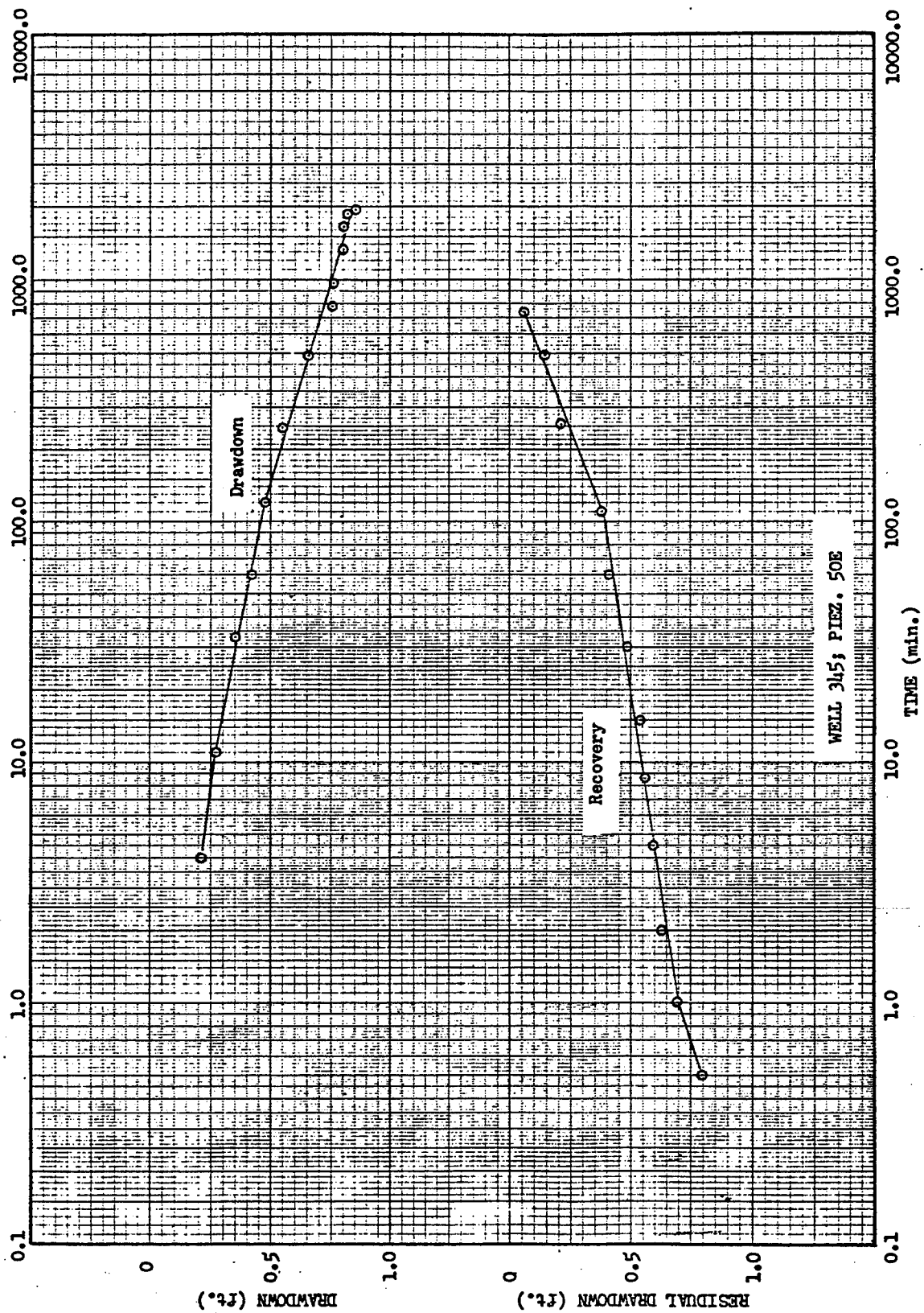


Figure 19. Drawdown and recovery versus time, Well 345; Piezometer 50E

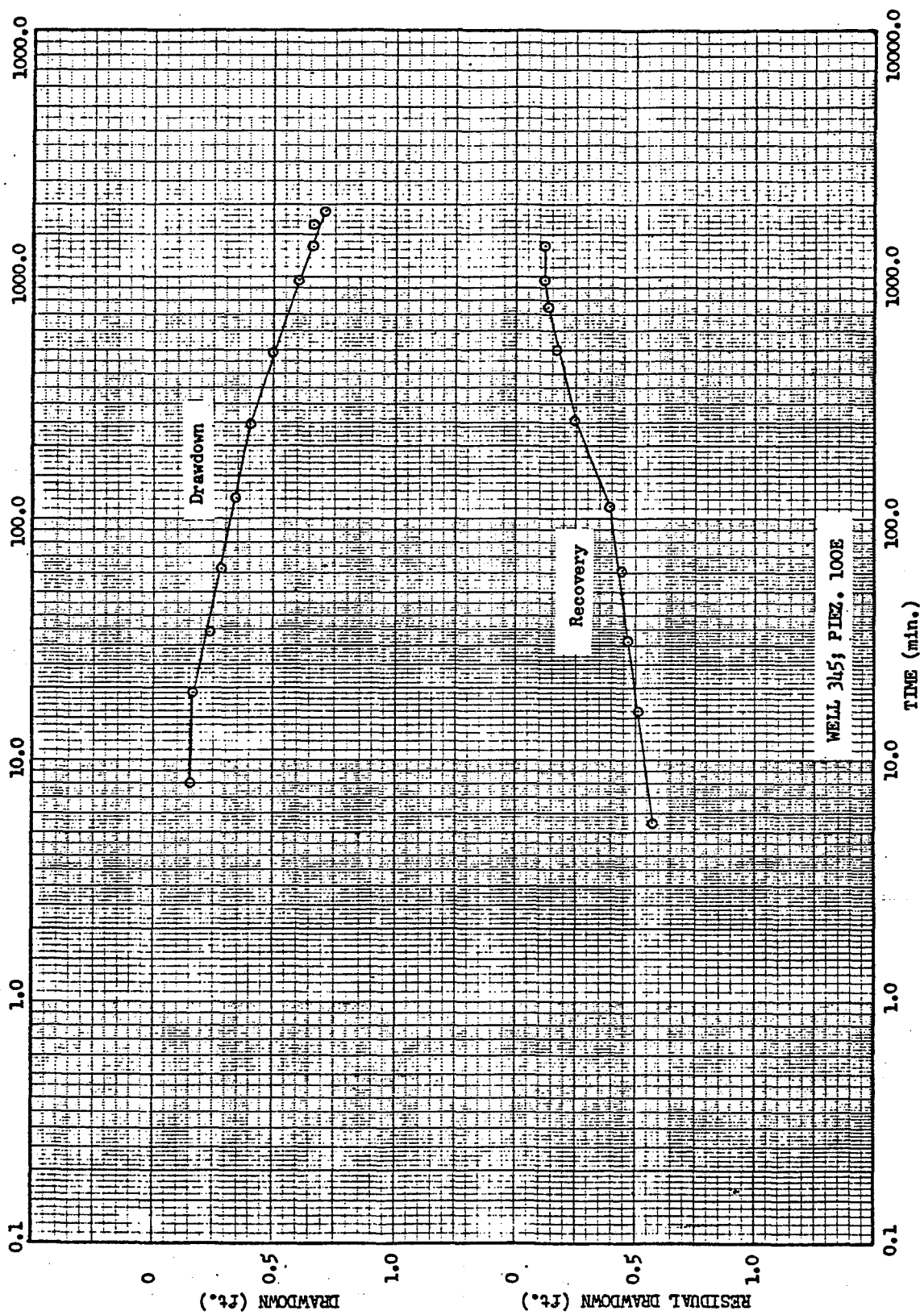


Figure 20. Drawdown and recovery versus time, Well 345; Piezometer 100E

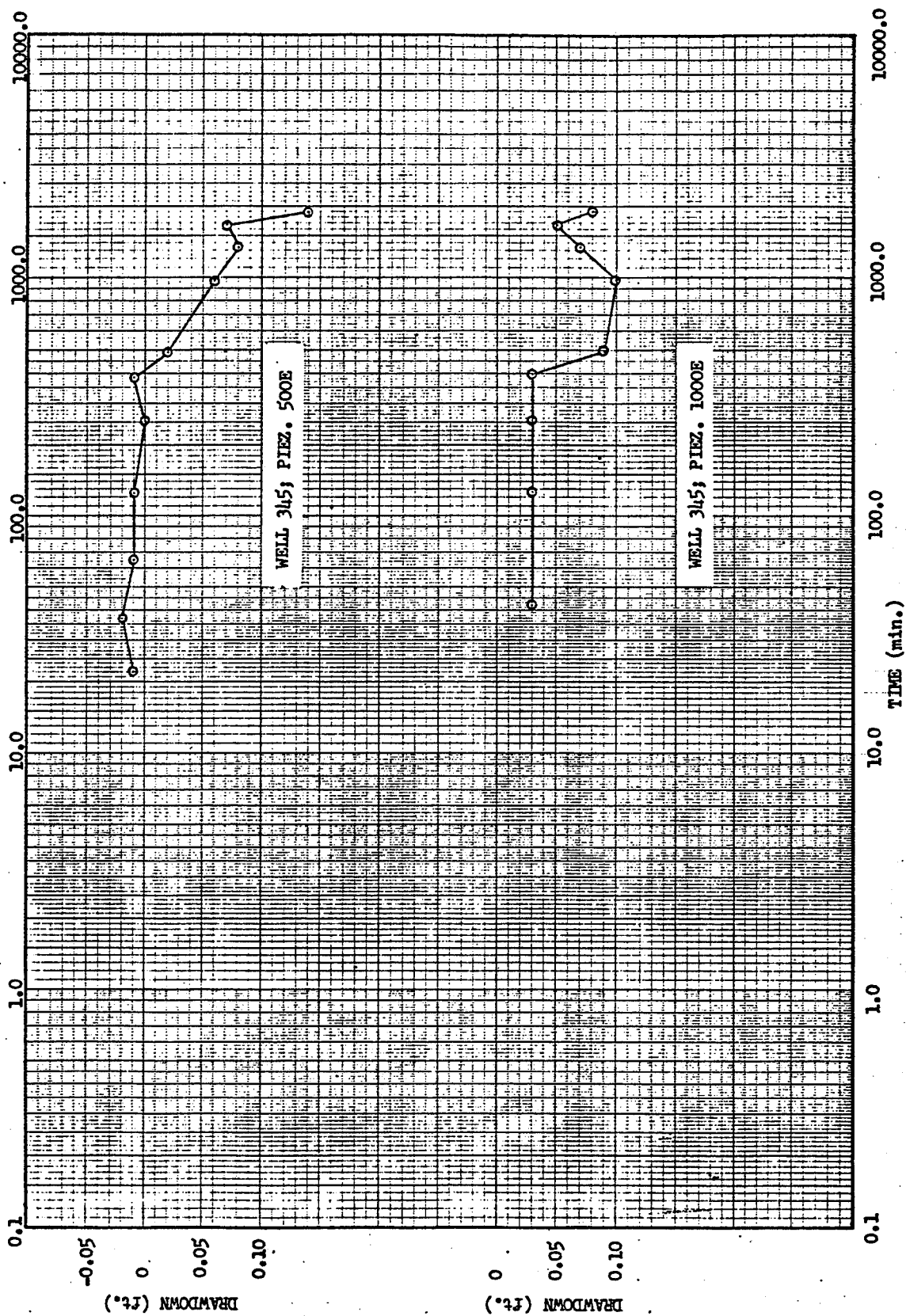


Figure 21. Drawdown versus time, Well 345; Piezometers 500E and 1000E

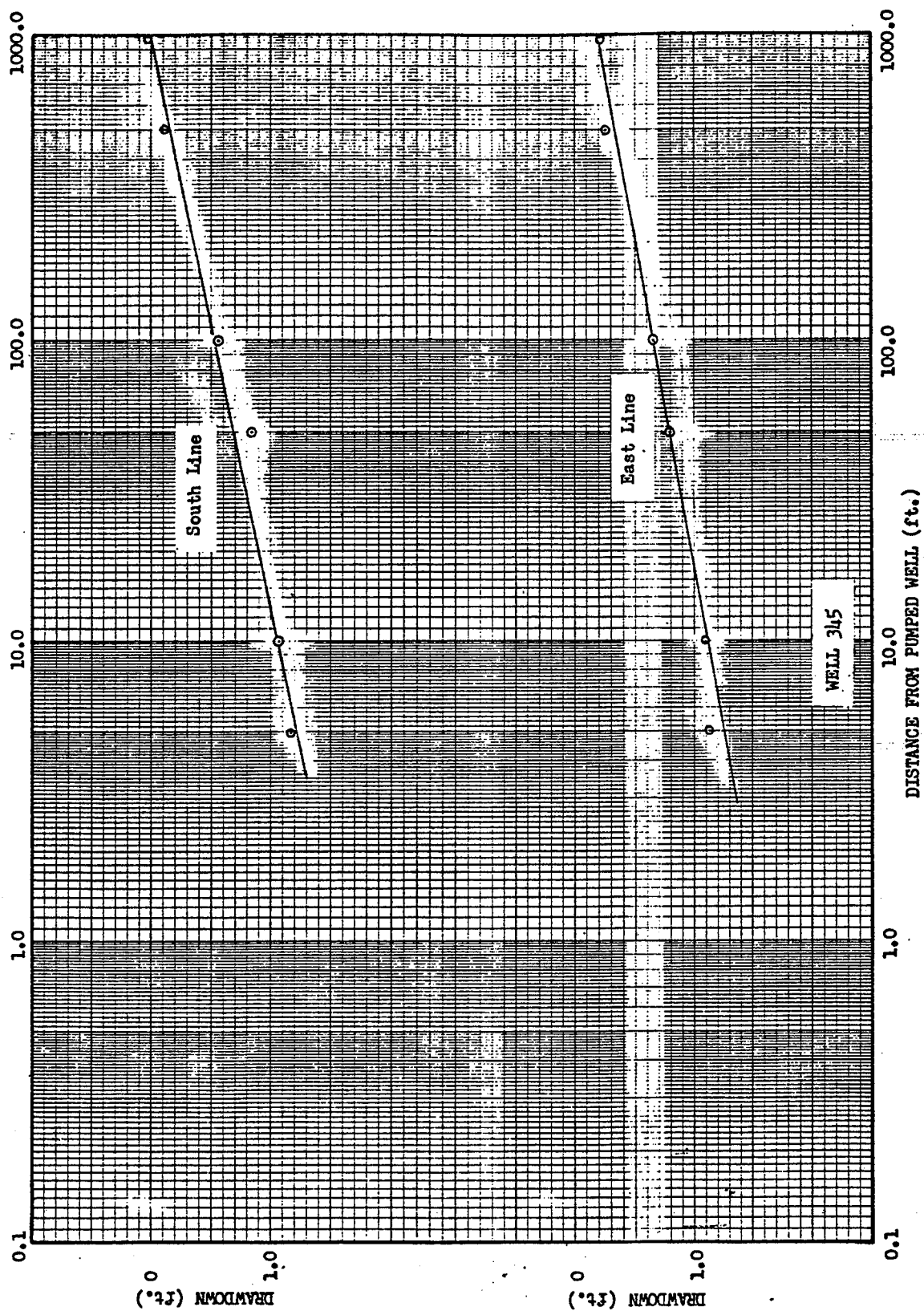


Figure 22. Drawdown versus distance from pumped well, Well 345

Table 2: Well 368
(Pumping rate - 35 GPM)

<u>Piezometer</u>	<u>Analysis Method</u>	<u>Transmissibility (gpd/ft)</u>	<u>Aquifer Thickness (ft)</u>	<u>Permeability (gpd/ft²)</u>
5 W	Theis, Jacob, Chow and Theis Recovery	44,000-84,160	6.8	6,470-12,400
10 W	Theis, Jacob, Chow and Theis Recovery	37,270-84,160	7.2	5,180-11,700
50 W	Theis, Jacob, Chow and Theis Recovery	48,300-92,400	4.8	10,000-19,250
100 W	Theis, Jacob, Chow and Theis Recovery	46,300-92,400	6.2	7,470-14,900
5 NE	Theis, Jacob, Chow and Theis Recovery	37,000-92,800	8.5	4,350-10,920
10 NE	Theis, Jacob, Chow and Theis Recovery	37,000-86,250	8.0	4,620-10,780
50 NE	Theis, Jacob, Chow and Theis Recovery	41,600-84,000	6.1	6,820-13,770
100 NE	Theis, Jacob, Chow and Theis Recovery	35,000-92,400	6.5	5,380-14,215
Well	Theis Recovery	72,470	6.0	12,000
West line	Jacob (Drawdown vs log of distance)	42,980	6.2	6,930
Northeast line	Jacob (Drawdown vs log of distance)	52,800	7.6	6,950

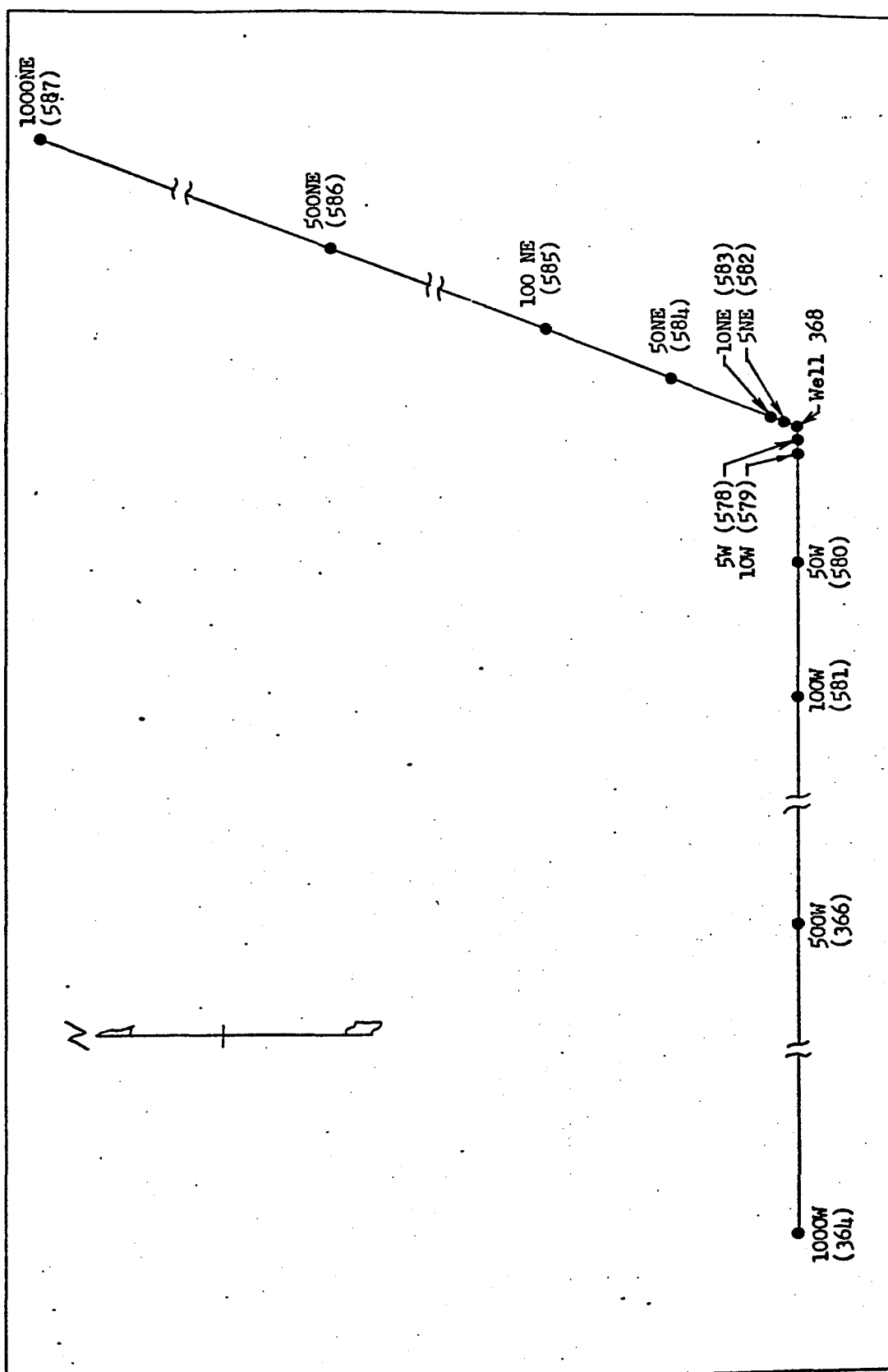


Figure 23. Piezometer layout for Test Well 368

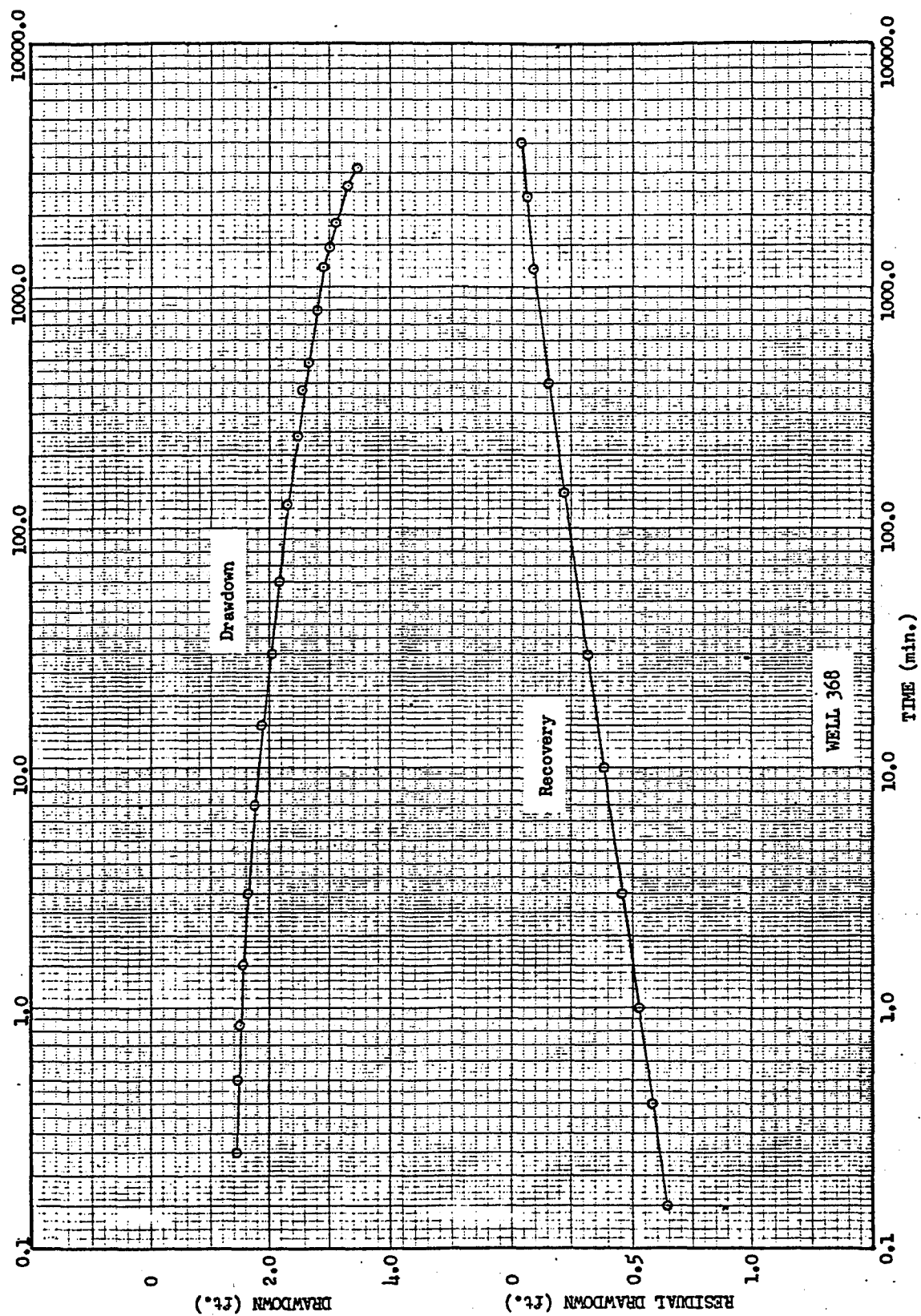


Figure 24. Drawdown and recovery versus time, Well 368.

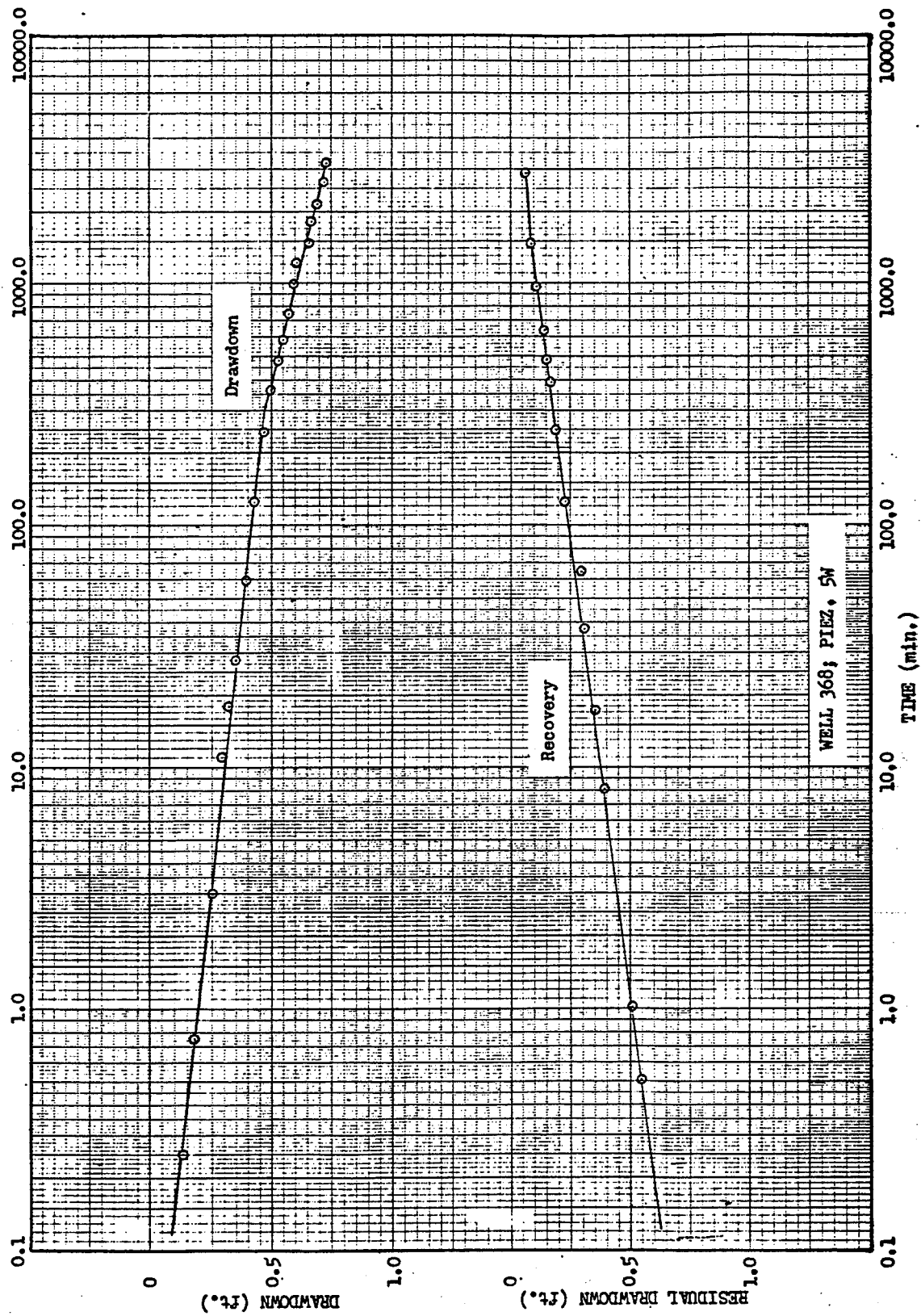


Figure 25. Drawdown and recovery versus time, Well 368; Piezometer 5W

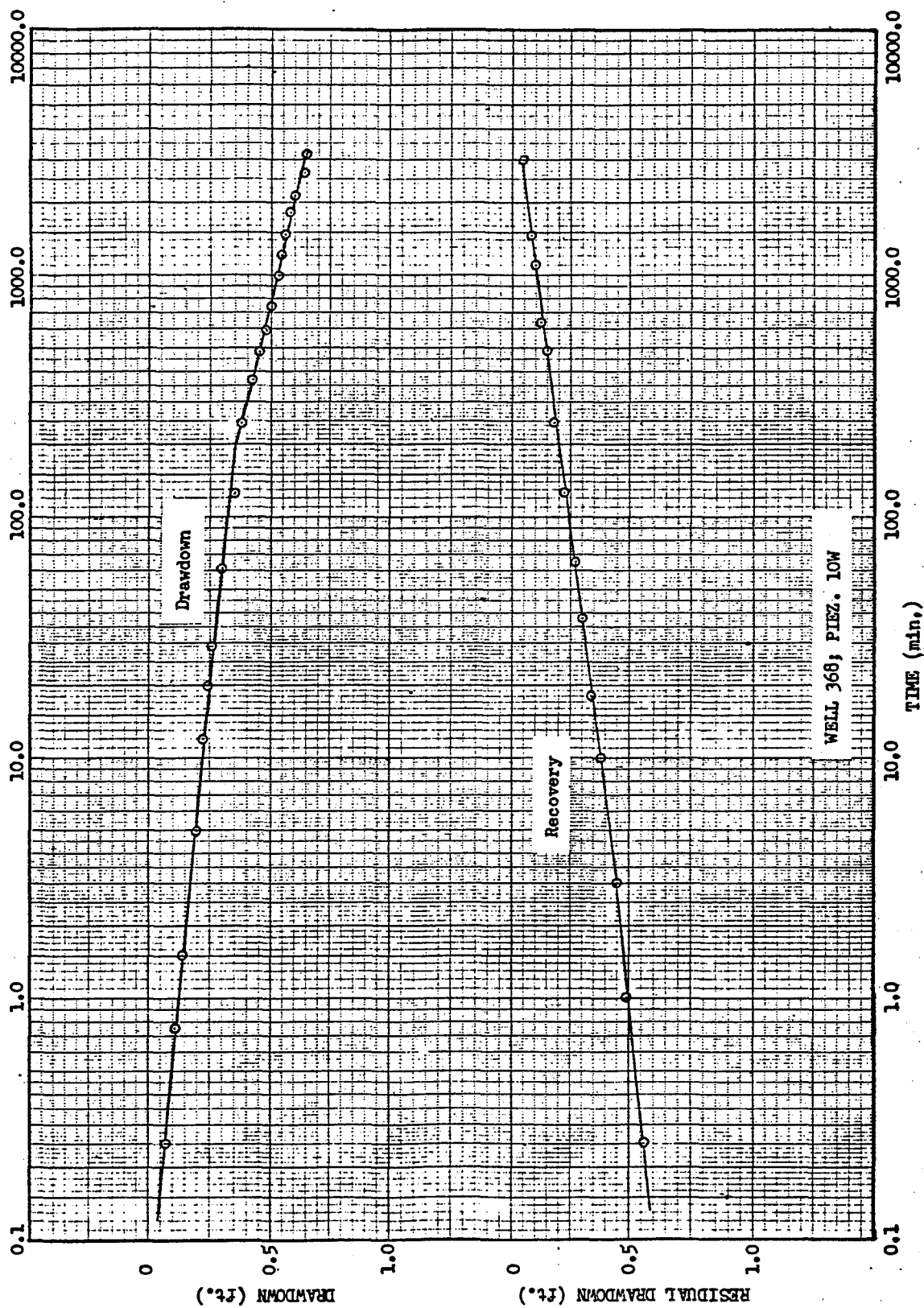


Figure 26. Drawdown and recovery versus time, Well 368; Piezometer 10W

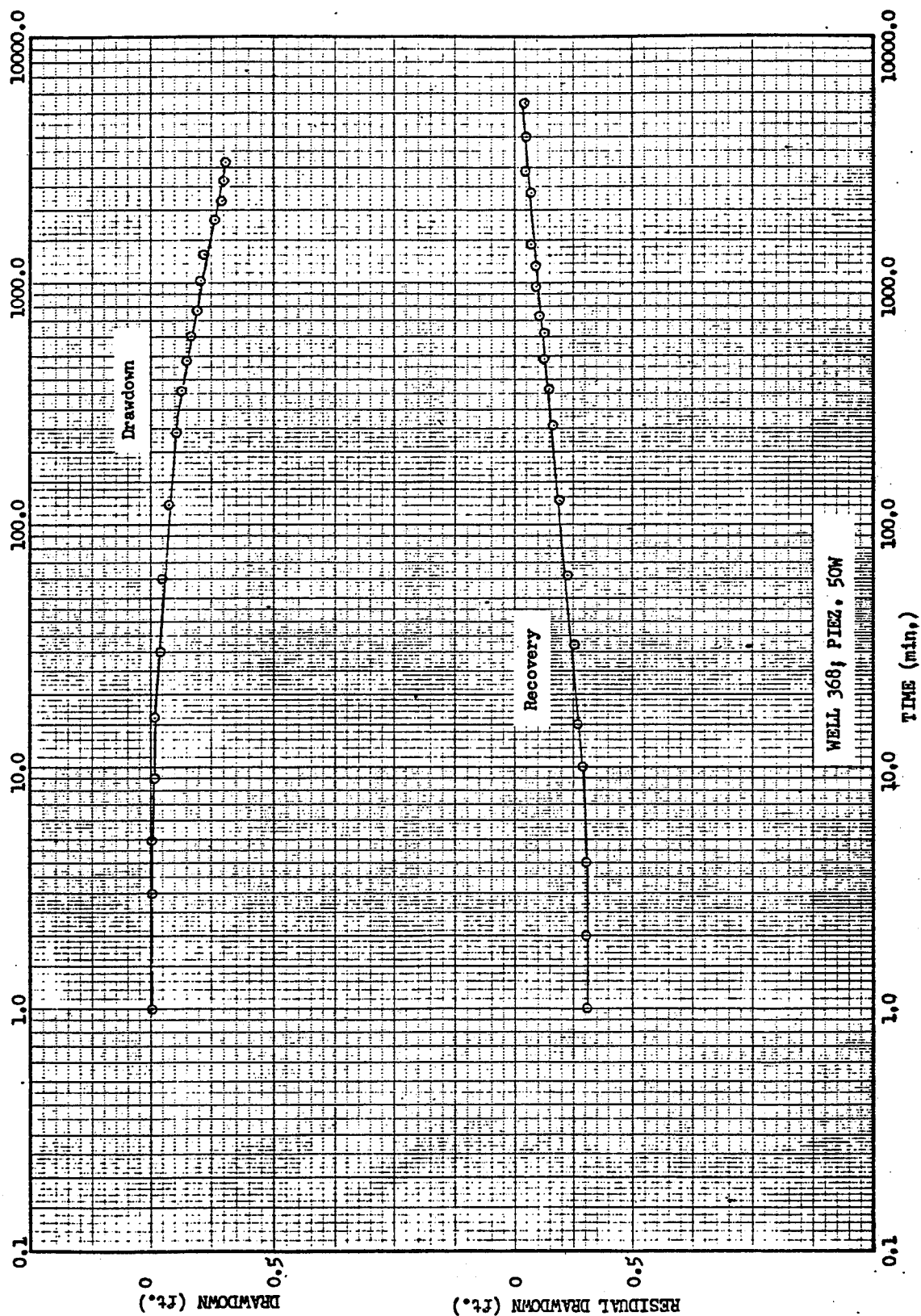


Figure 27. Drawdown and recovery versus time, Well 368; Piezometer 50W

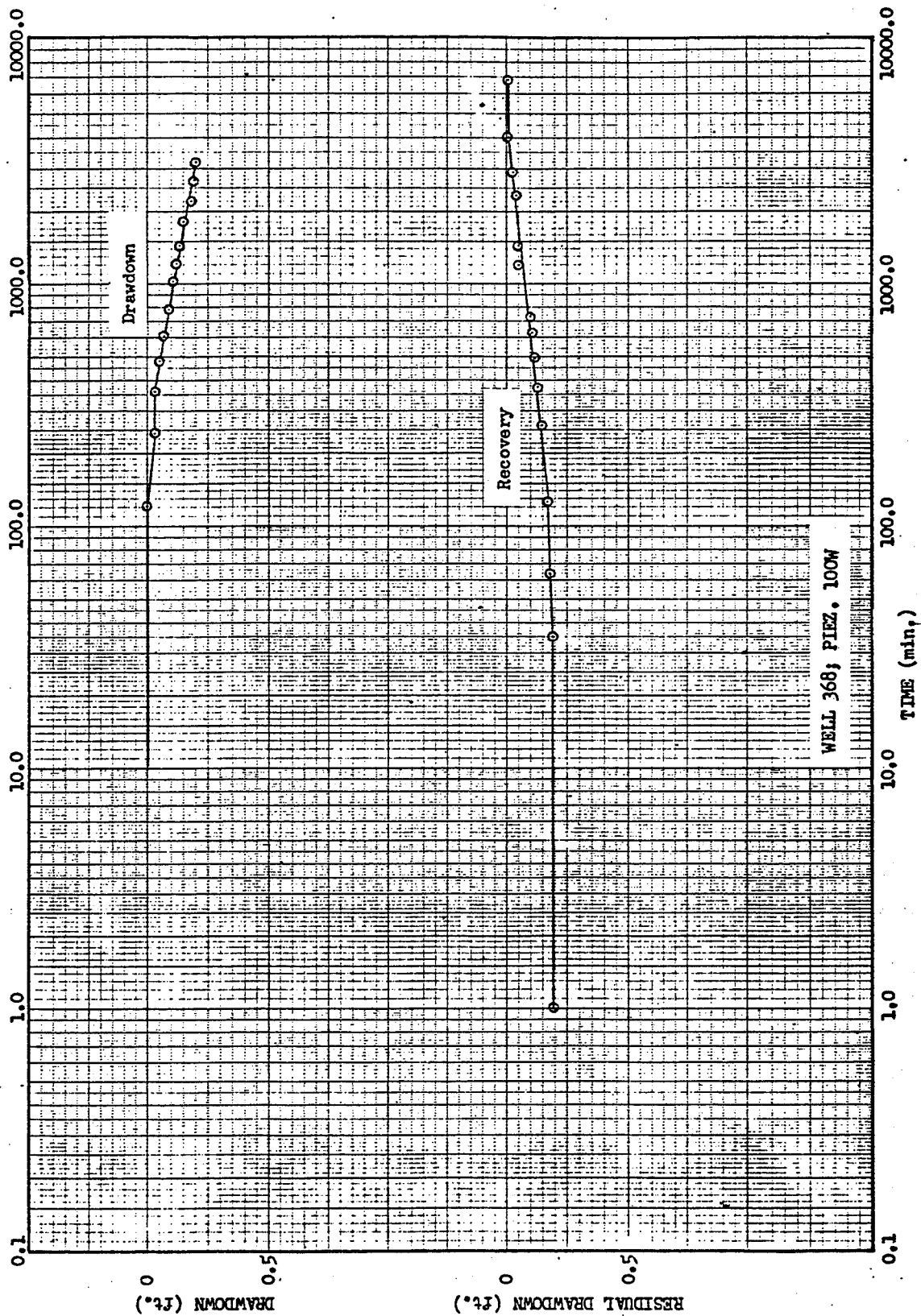


Figure 28. Drawdown and recovery versus time, Well 368; Piezometer 100W

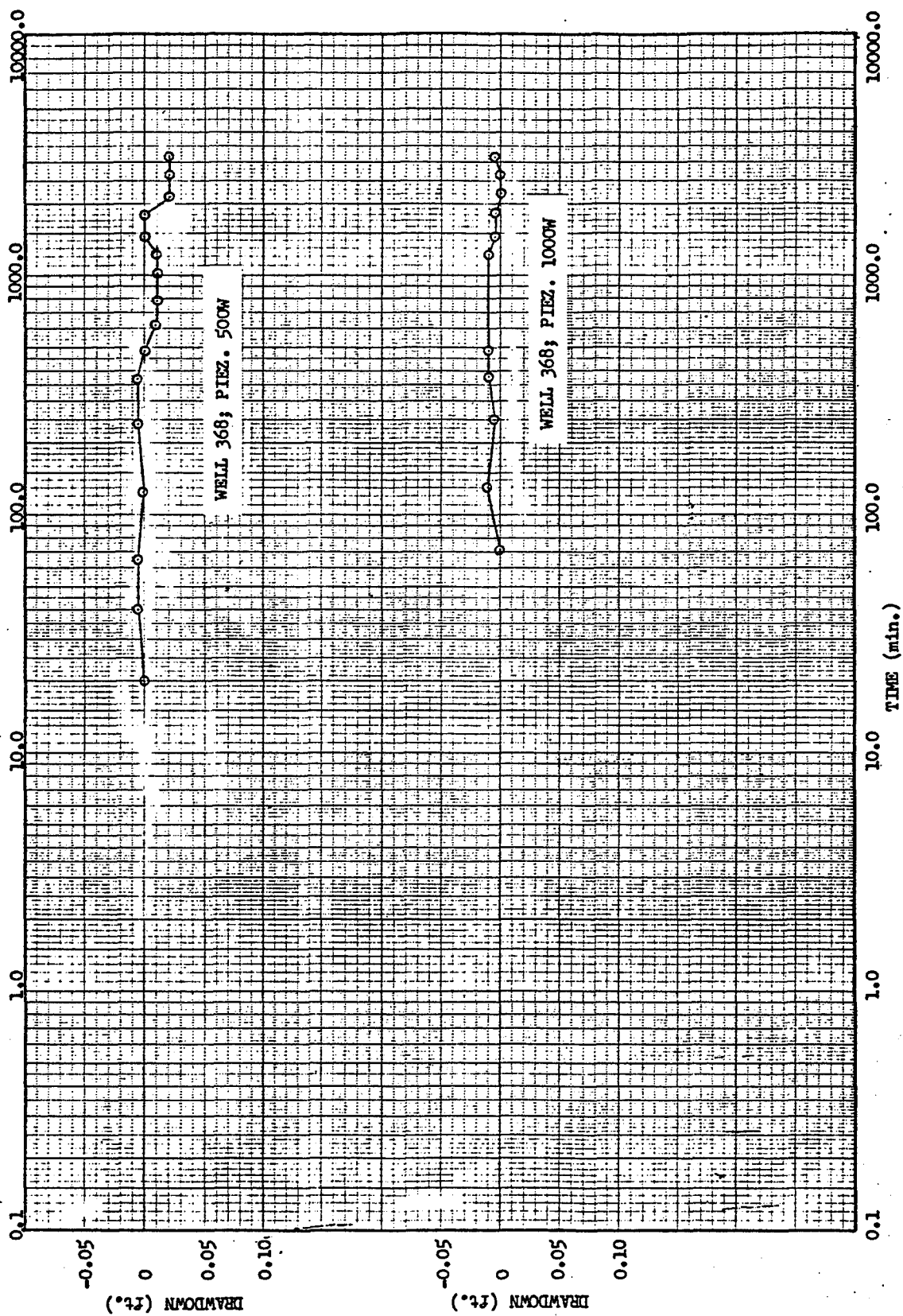


Figure 29. Drawdown versus time, Well 368; Piezometers 500W and 1000W

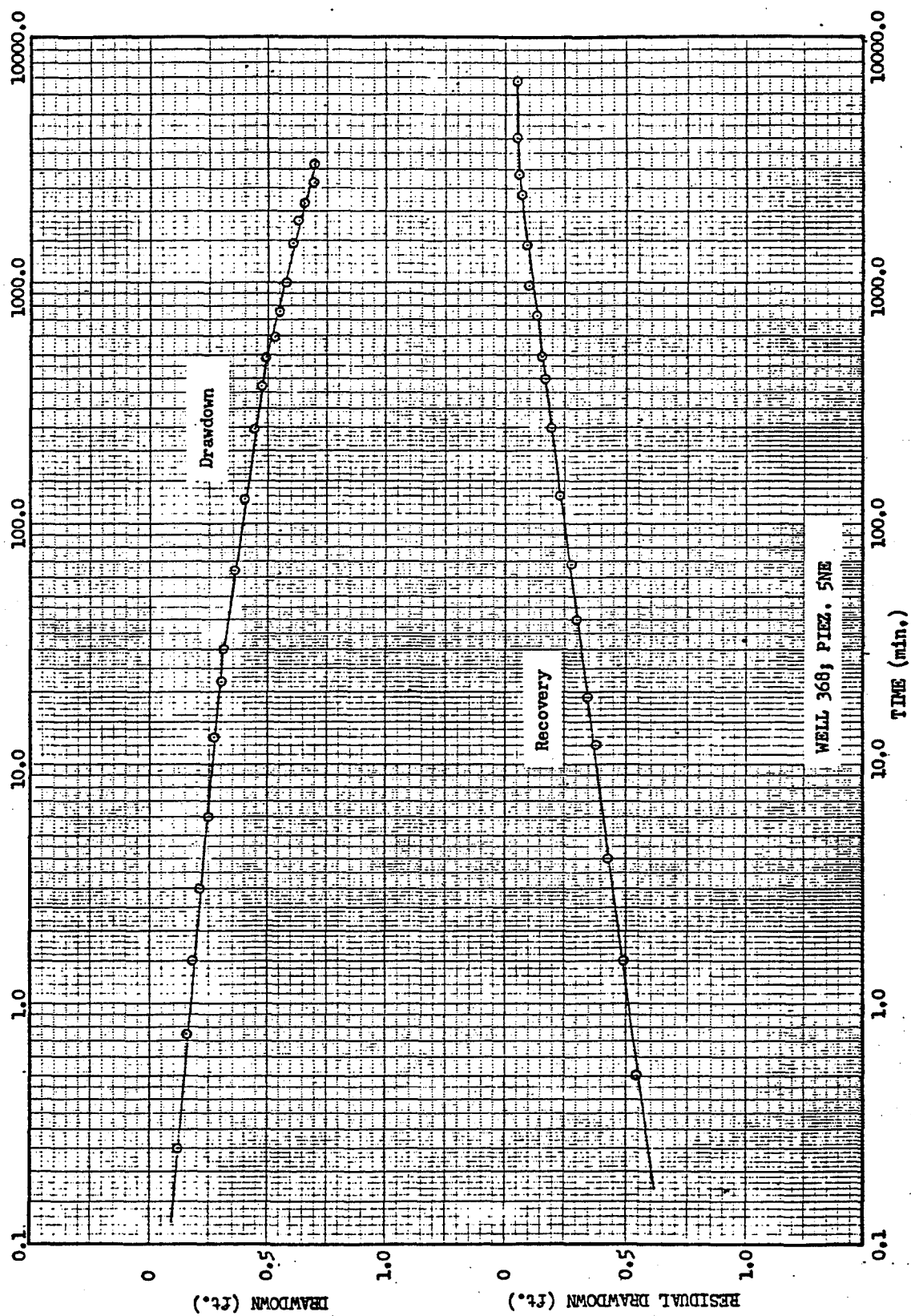


Figure 30. Drawdown and recovery versus time, Well 368; Piezometer 5NE

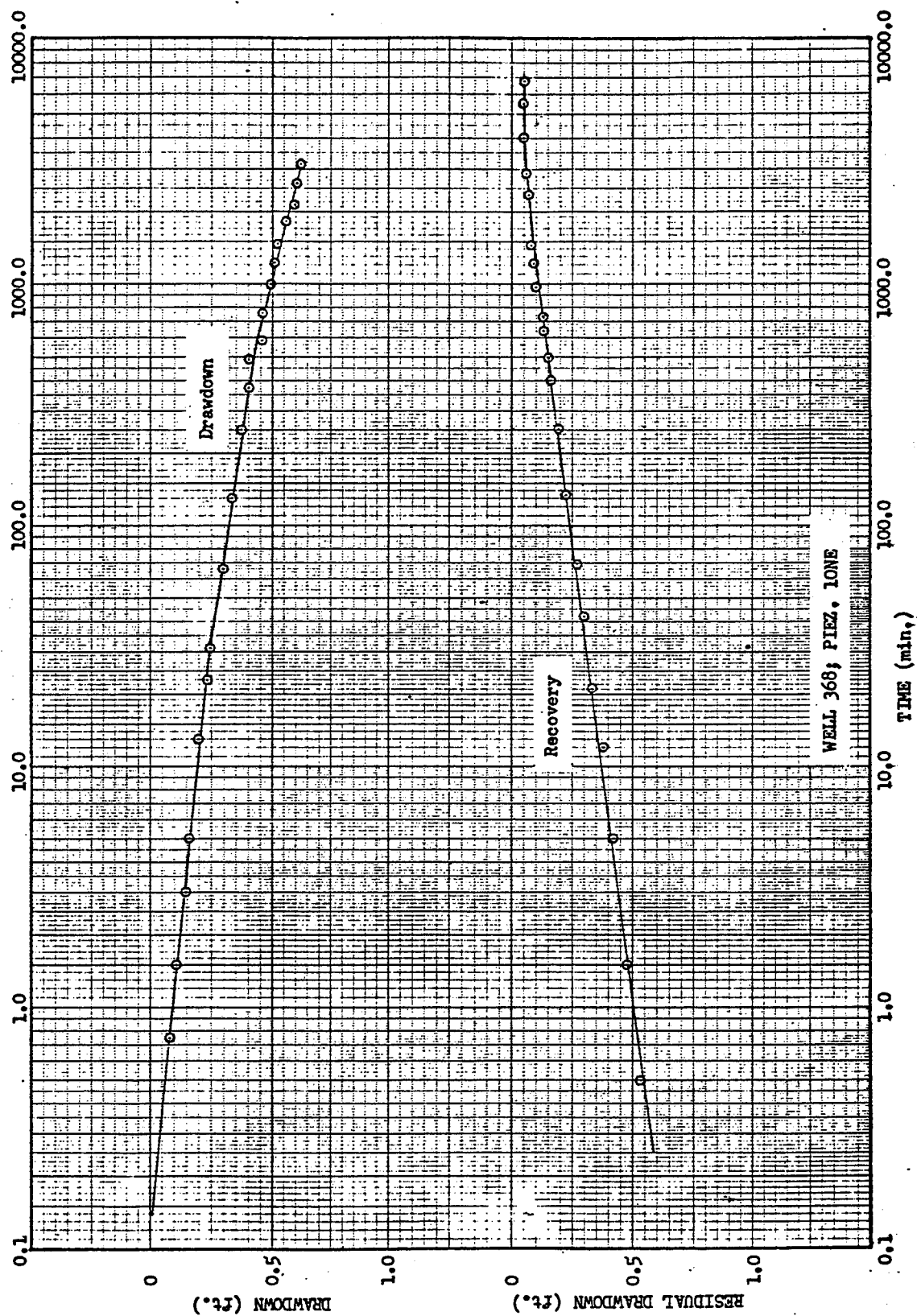


Figure 31. Drawdown and recovery versus time, Well 368; Piezometer 10NE

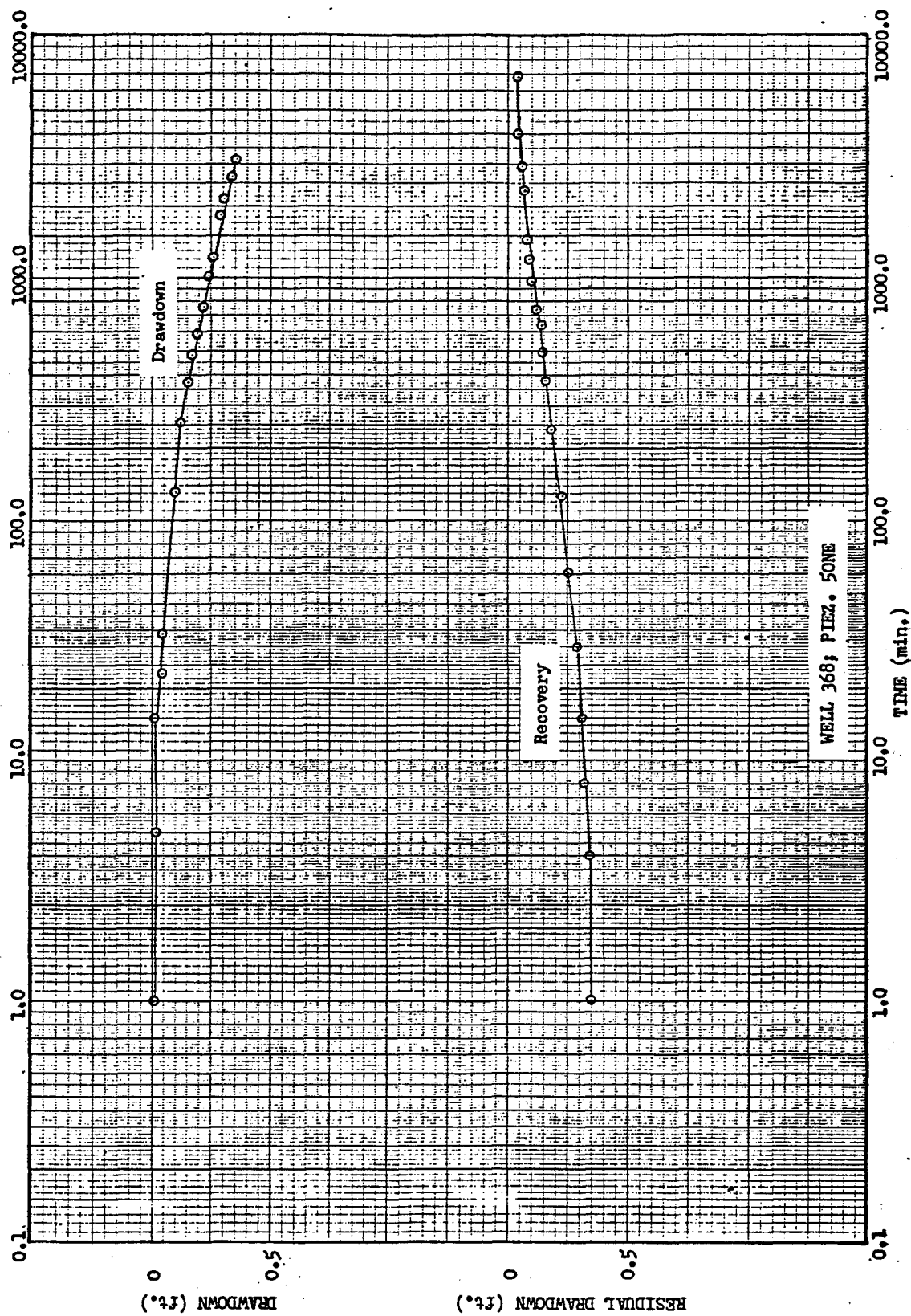


Figure 32. Drawdown and recovery versus time, Well 368; Piezometer 50NE

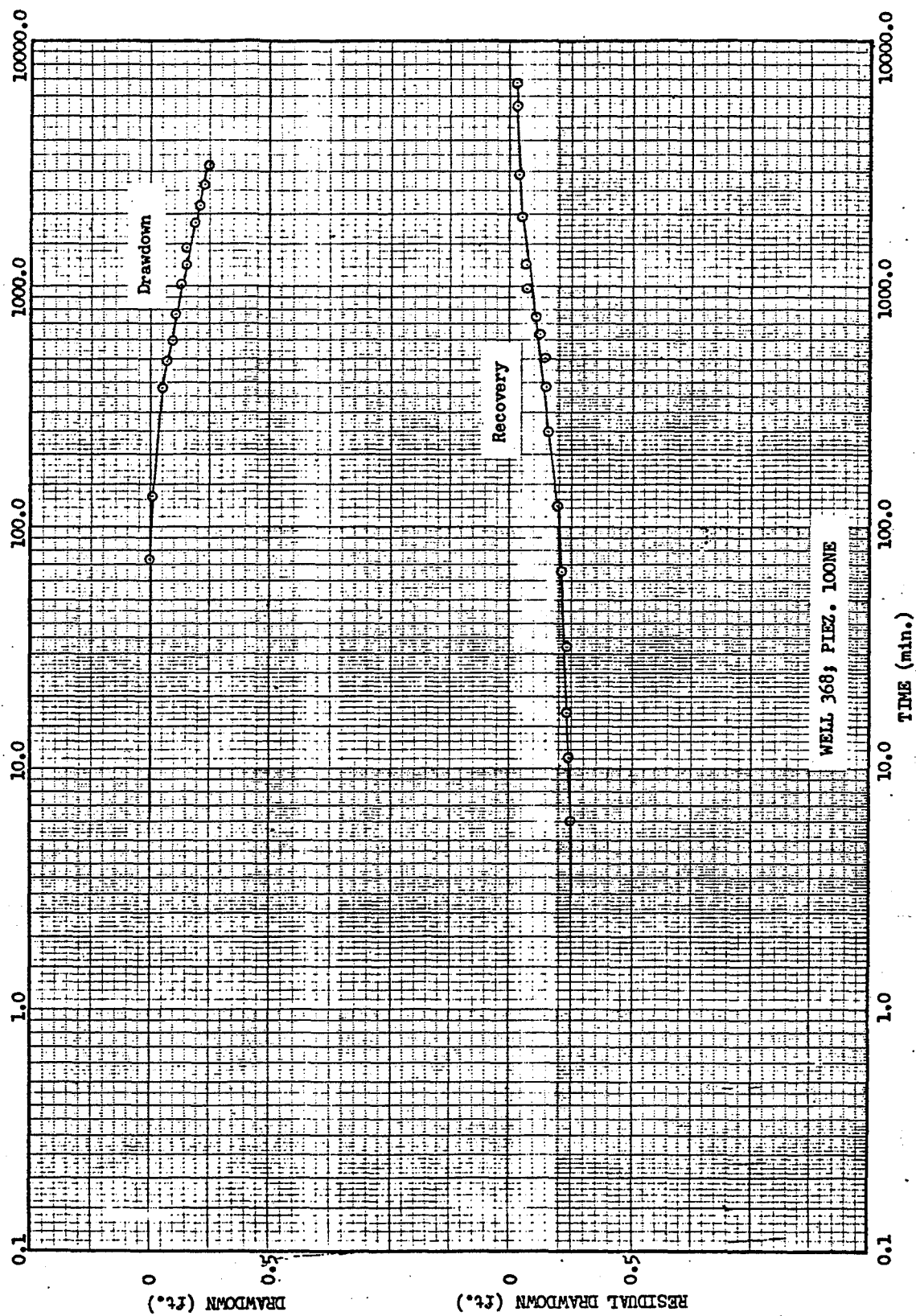


Figure 33. Drawdown and recovery versus time, Well 368; Piezometer 100NE

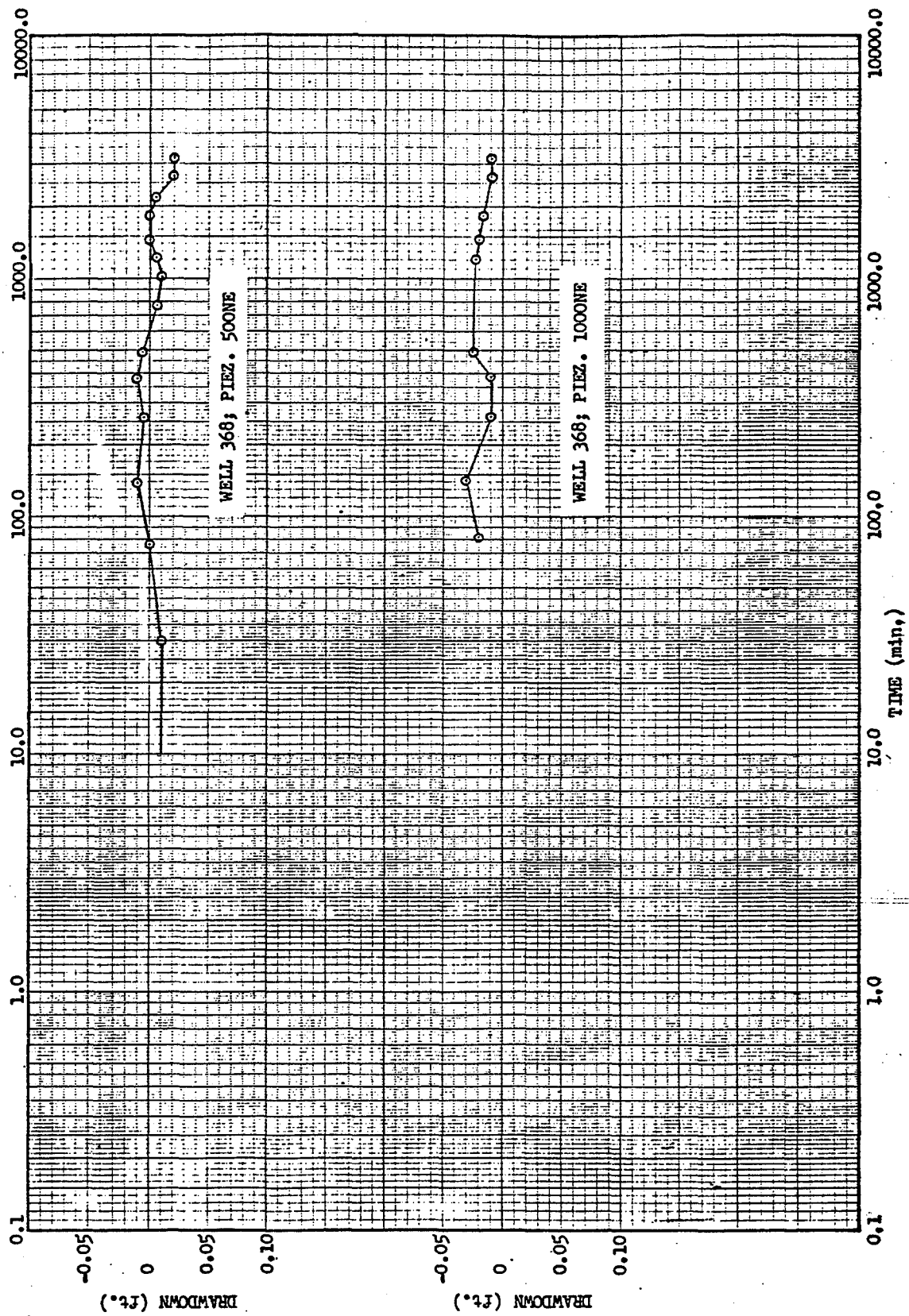


Figure 34. Drawdown versus time, Well 368; Piezometers 500NE and 1000NE

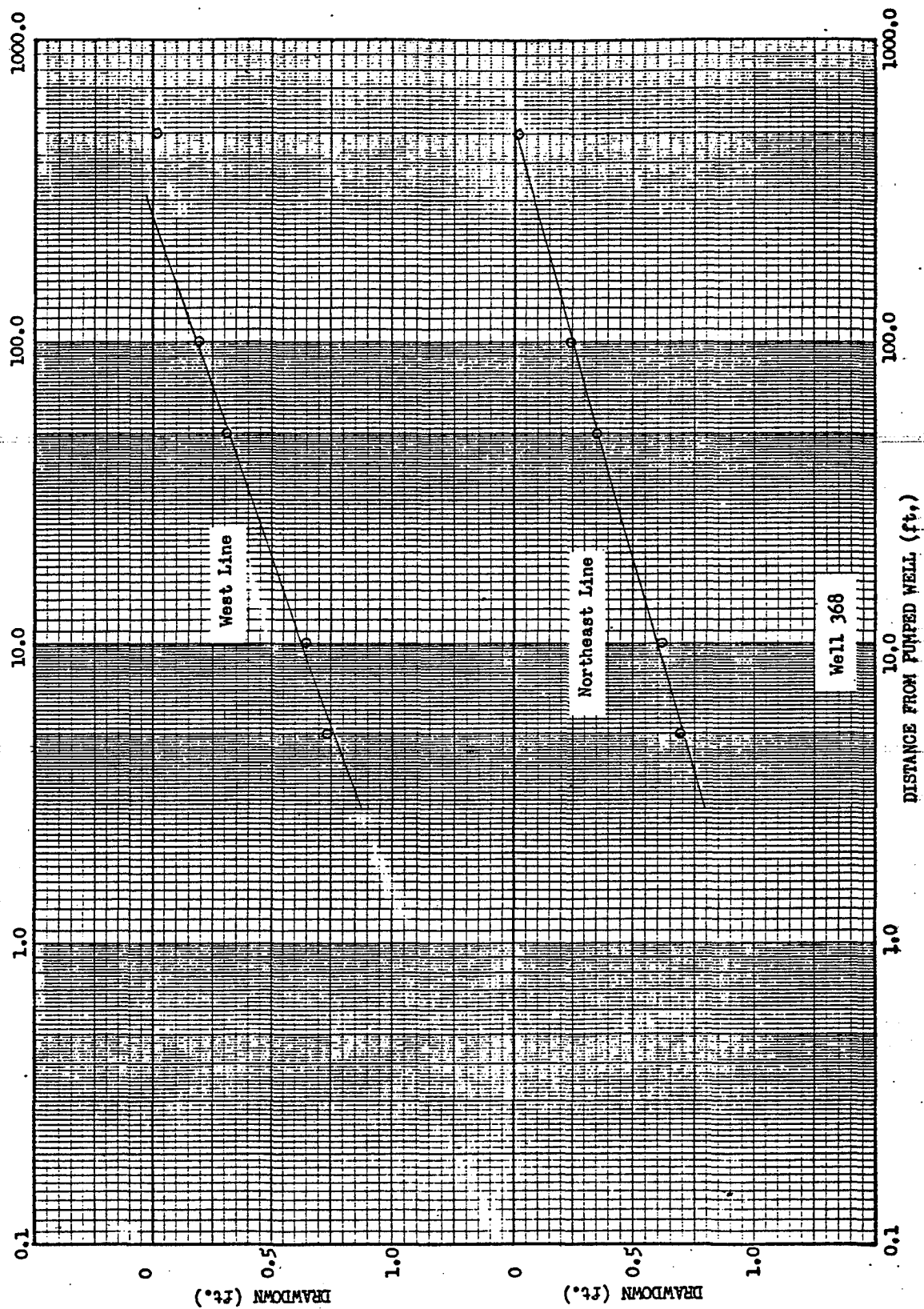


Figure 35. Drawdown versus distance from pumped well, Well 368

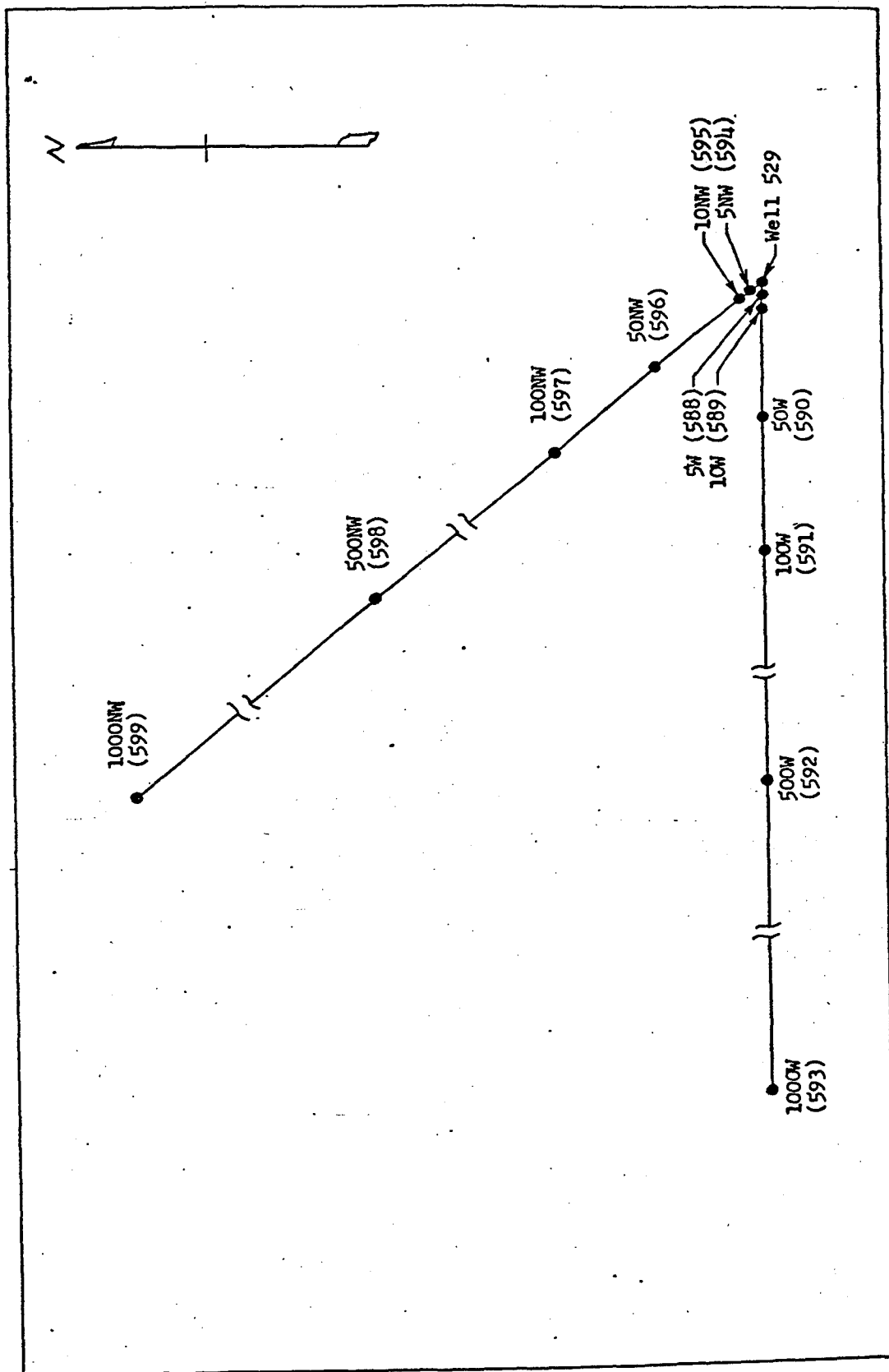


Figure 36. Piezometer layout for Test Well 529

Table 3: Well 529
(Pumping rate - 60 GPM)

<u>Piezometer</u>	<u>Analysis Method</u>	<u>Transmissibility (gpd/ft)</u>	<u>Aquifer Thickness (ft)</u>	<u>Permeability (gpd/ft²)</u>
5 W	Theis, Jacob, Chow and Theis Recovery	79,600- 99,000	11.3	7,040- 8,760
10 W	Theis, Jacob, Chow and Theis Recovery	88,000-108,700	11.1	7,720- 9,790
50 W	Theis, Jacob, Chow and Theis Recovery	71,400- 79,200	9.4	7,600- 8,425
100 W	Theis, Jacob, Chow and Theis Recovery	66,700-113,000	7.2	9,260-15,700
5 NW	Theis, Jacob, Chow and Theis Recovery	72,600- 99,000	11.4	6,320- 8,680
10 NW	Theis, Jacob, Chow and Theis Recovery	77,500-113,100	11.4	6,800- 9,920
50 NW	Theis, Jacob, Chow and Theis Recovery	79,400- 99,000	10.8	7,350- 9,170
100 NW	Theis, Jacob, Chow and Theis Recovery	82,800-132,000	10.0	8,280-13,200
Well	Theis Recovery	132,000	11.5	11,500
West line	Jacob (Drawdown vs log of distance)	87,400	10.6	8,250
Northwest line	Jacob (Drawdown vs log of distance)	73,300	11.1	6,600

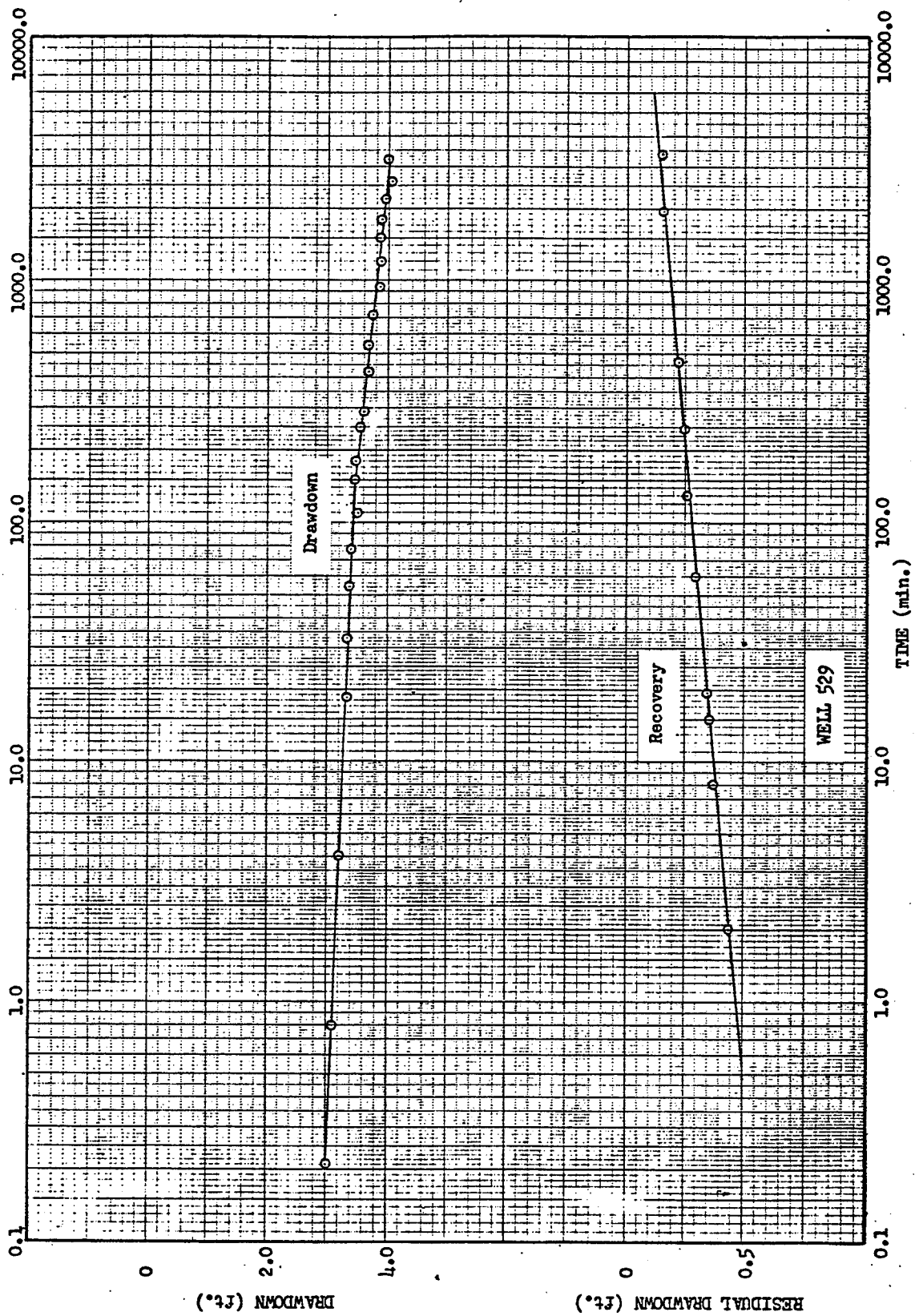


Figure 37. Drawdown and recovery versus time, Well 529

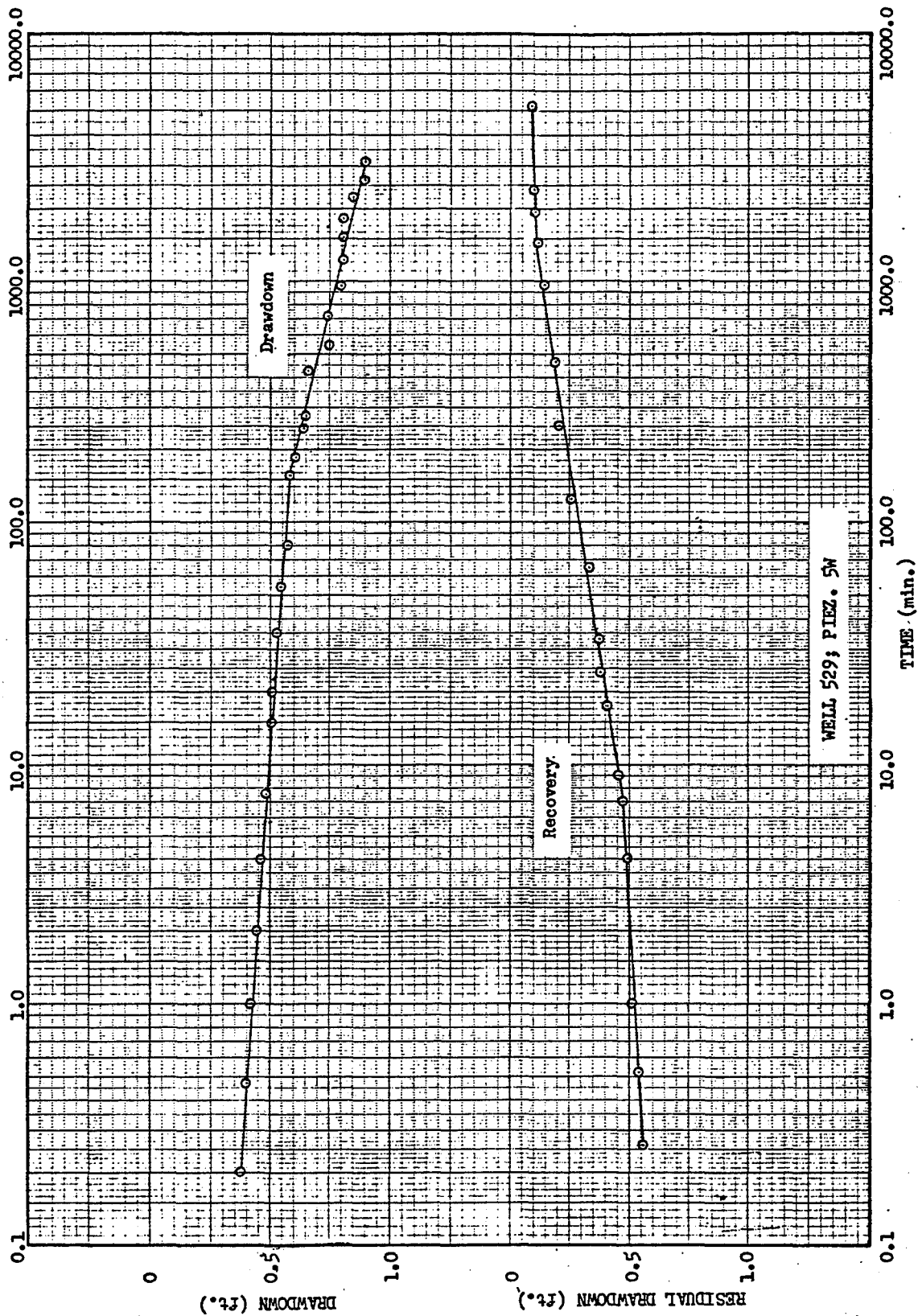


Figure 38. Drawdown and recovery versus time, Well 529; Piezometer 5W

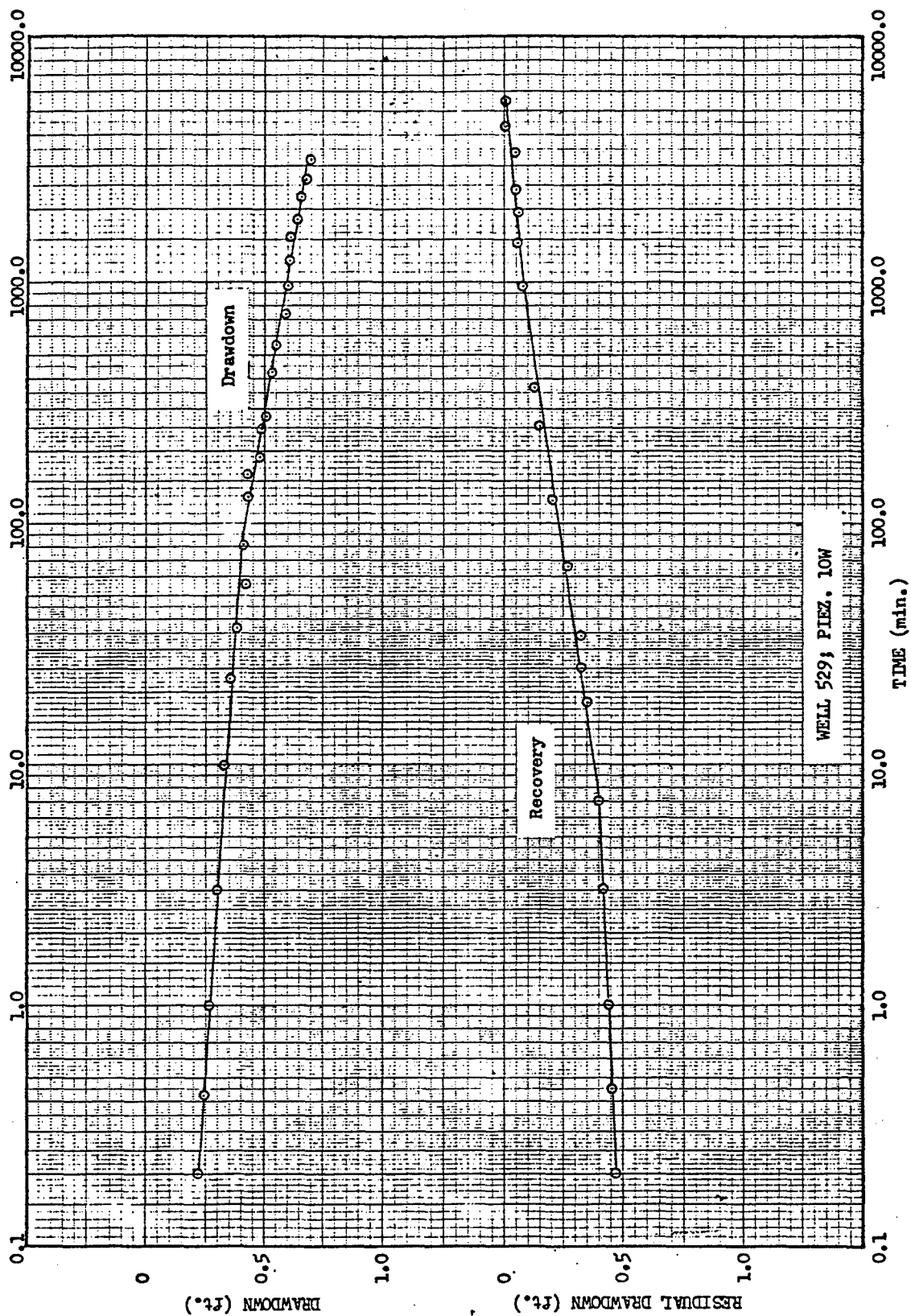


Figure 39. Drawdown and recovery versus time, Well 529; Piezometer 10W

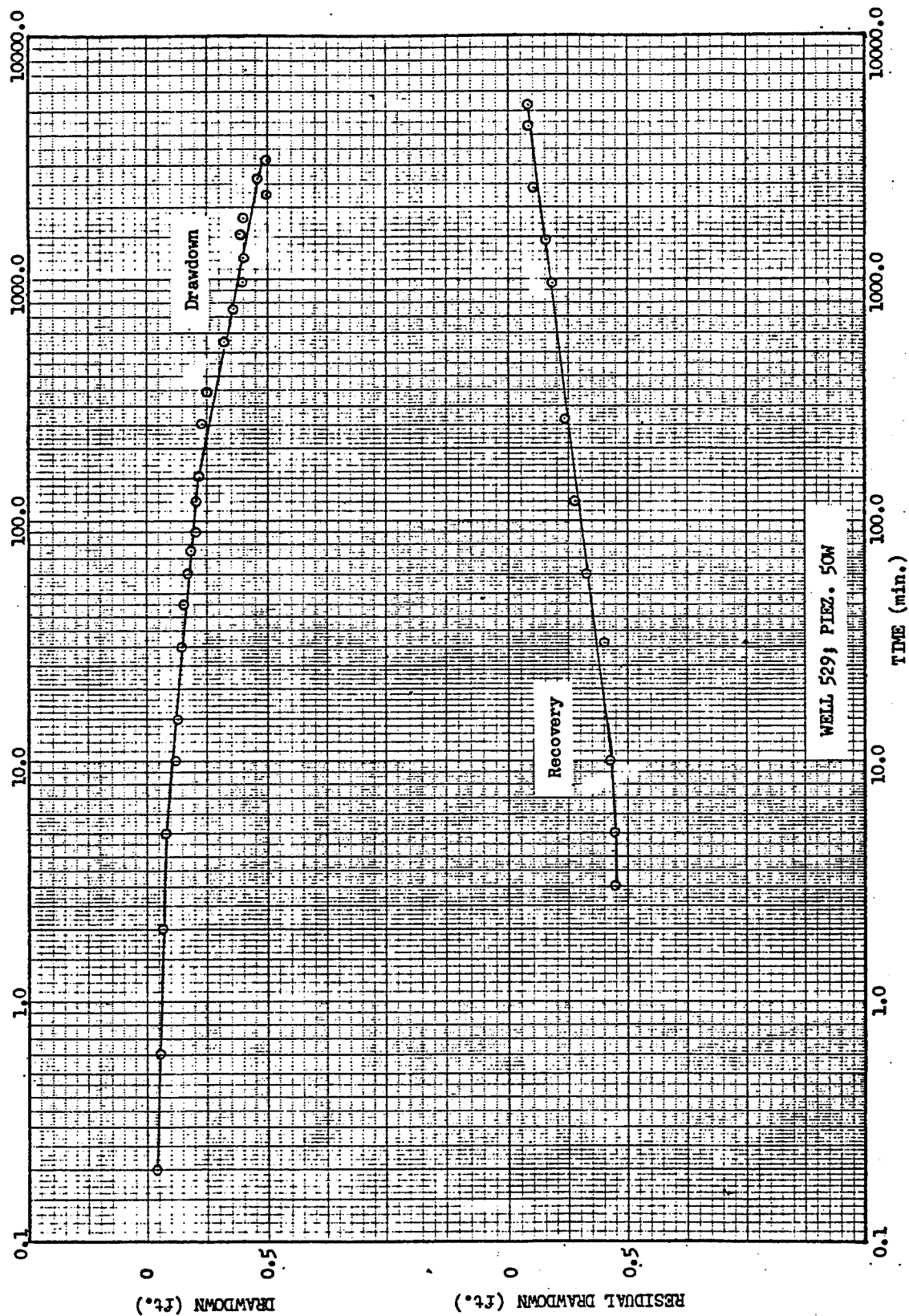


Figure 40. Drawdown and recovery versus time, Well 529; Piezometer 50W

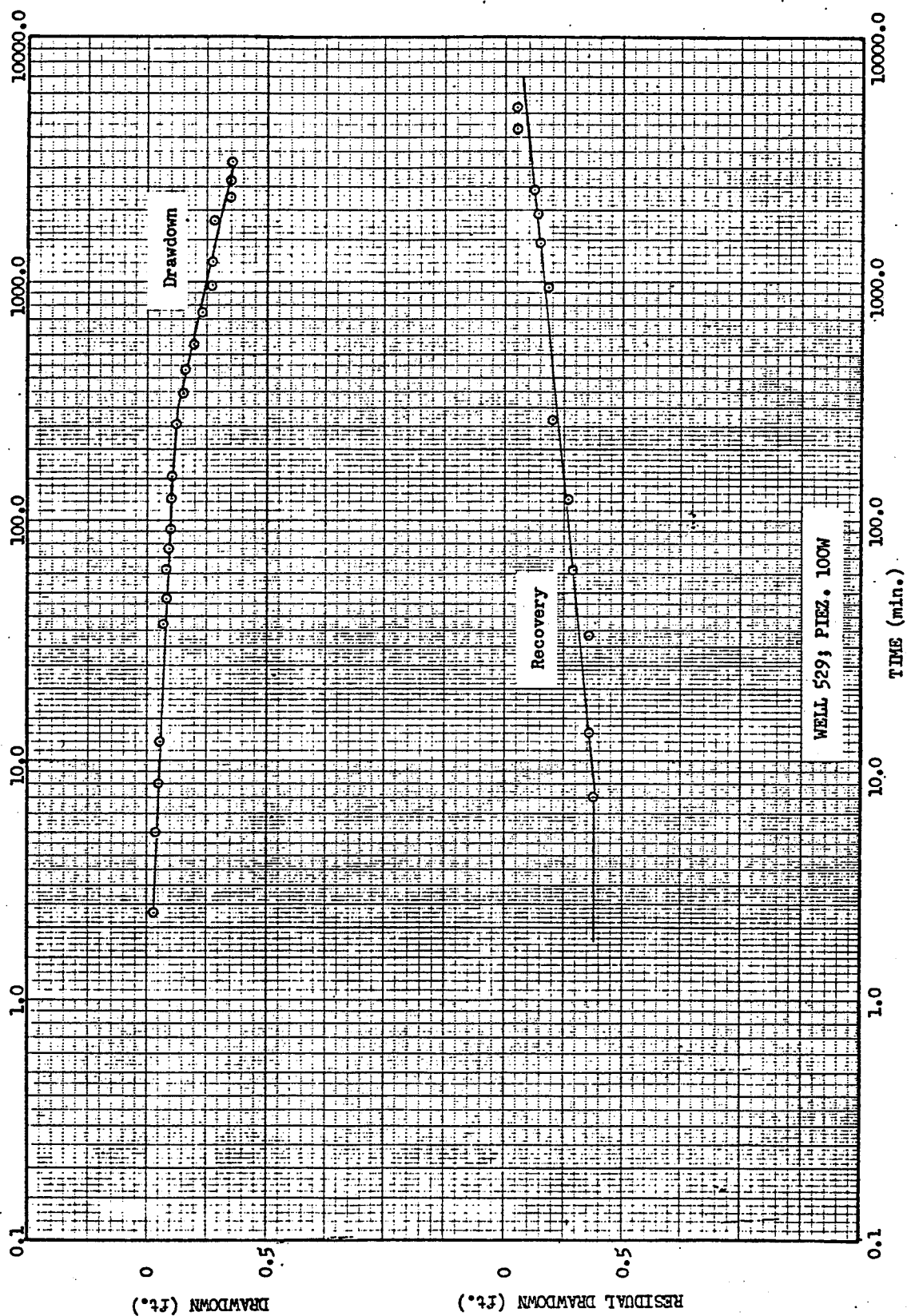


Figure 41. Drawdown and recovery versus time, Well 529; Piezometer 100W

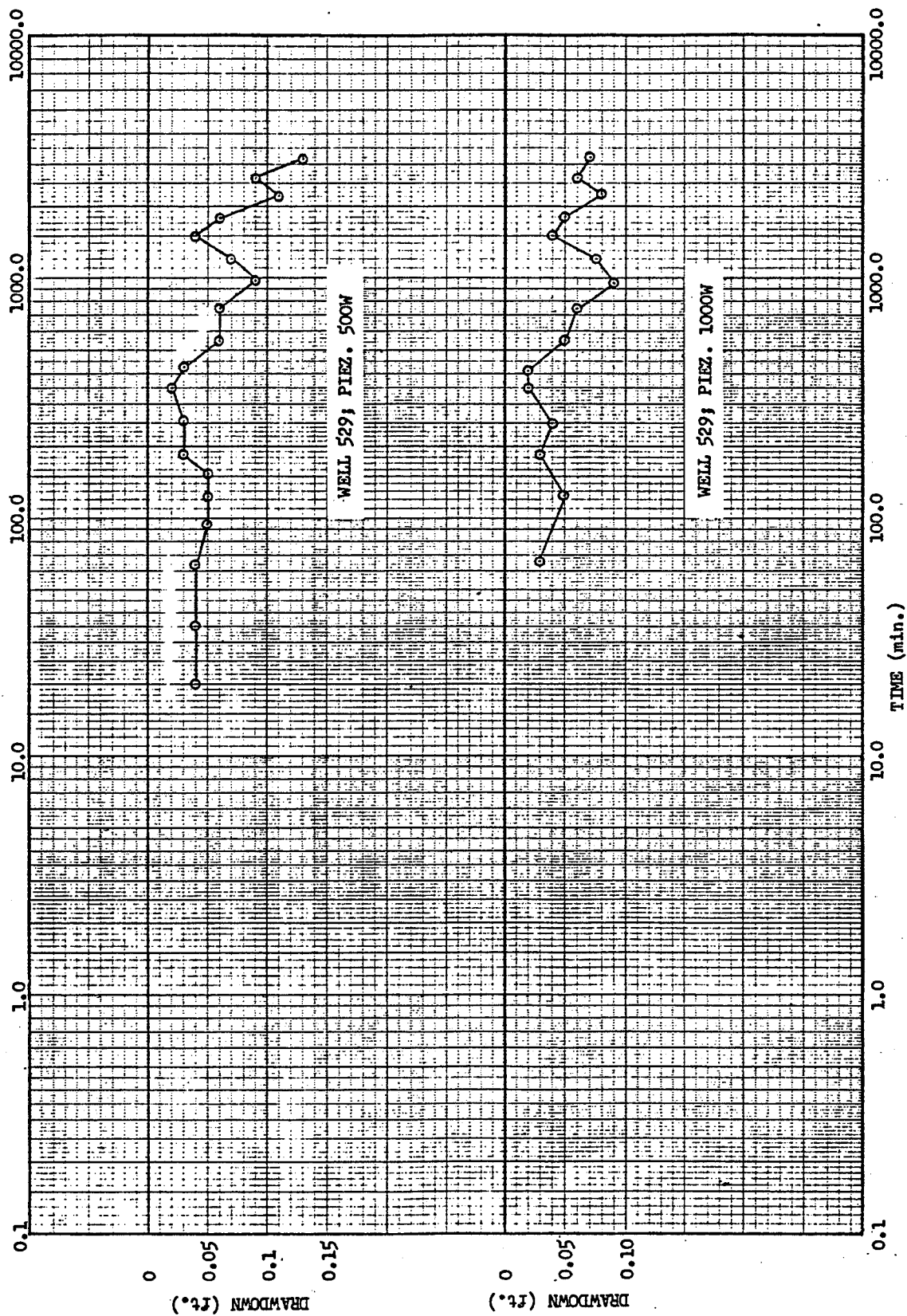


Figure 42. Drawdown versus time, Well 529; Piezometers 500W and 1000W

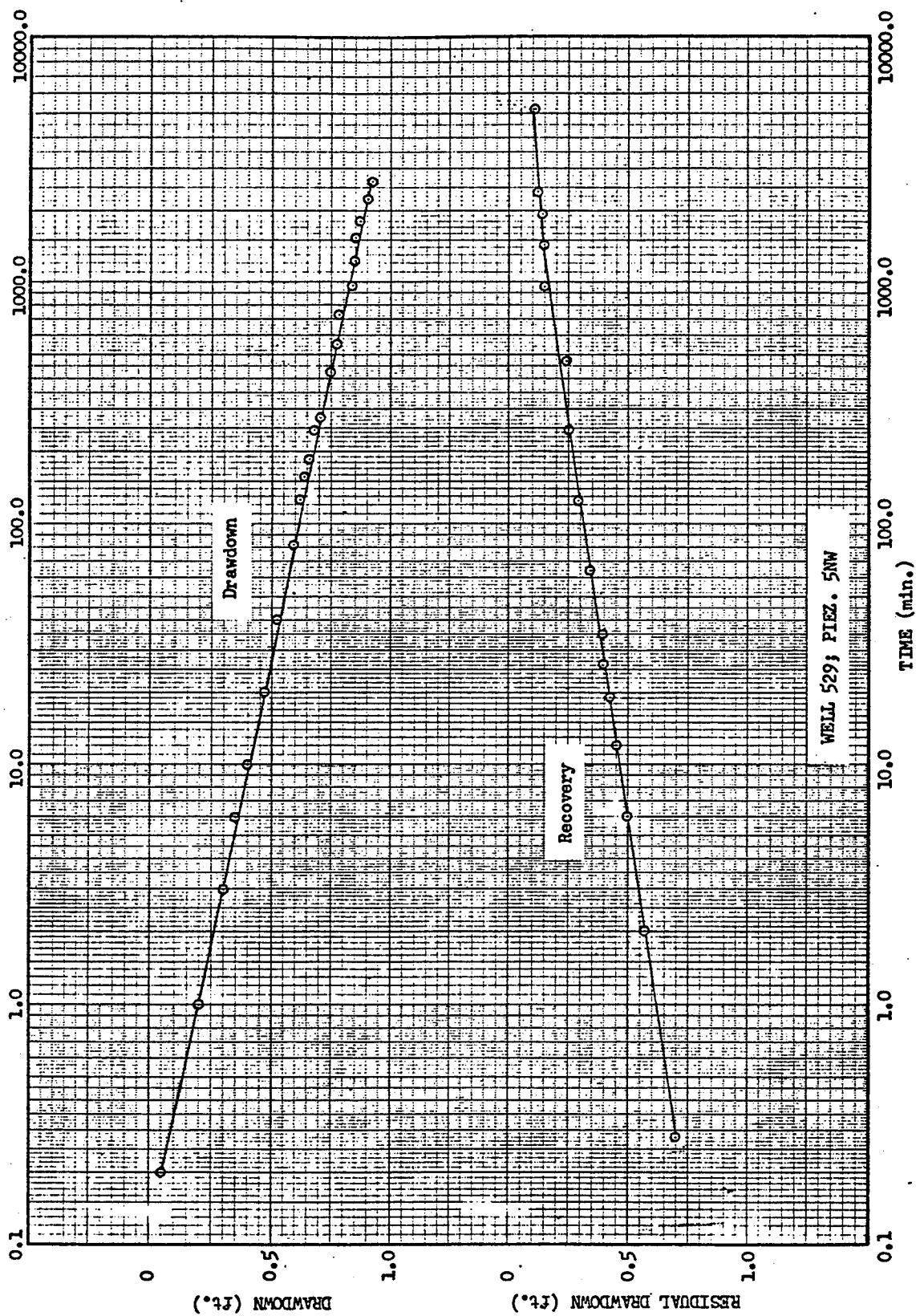


Figure 43. Drawdown and recovery versus time, Well 529; Piezometer 5NW

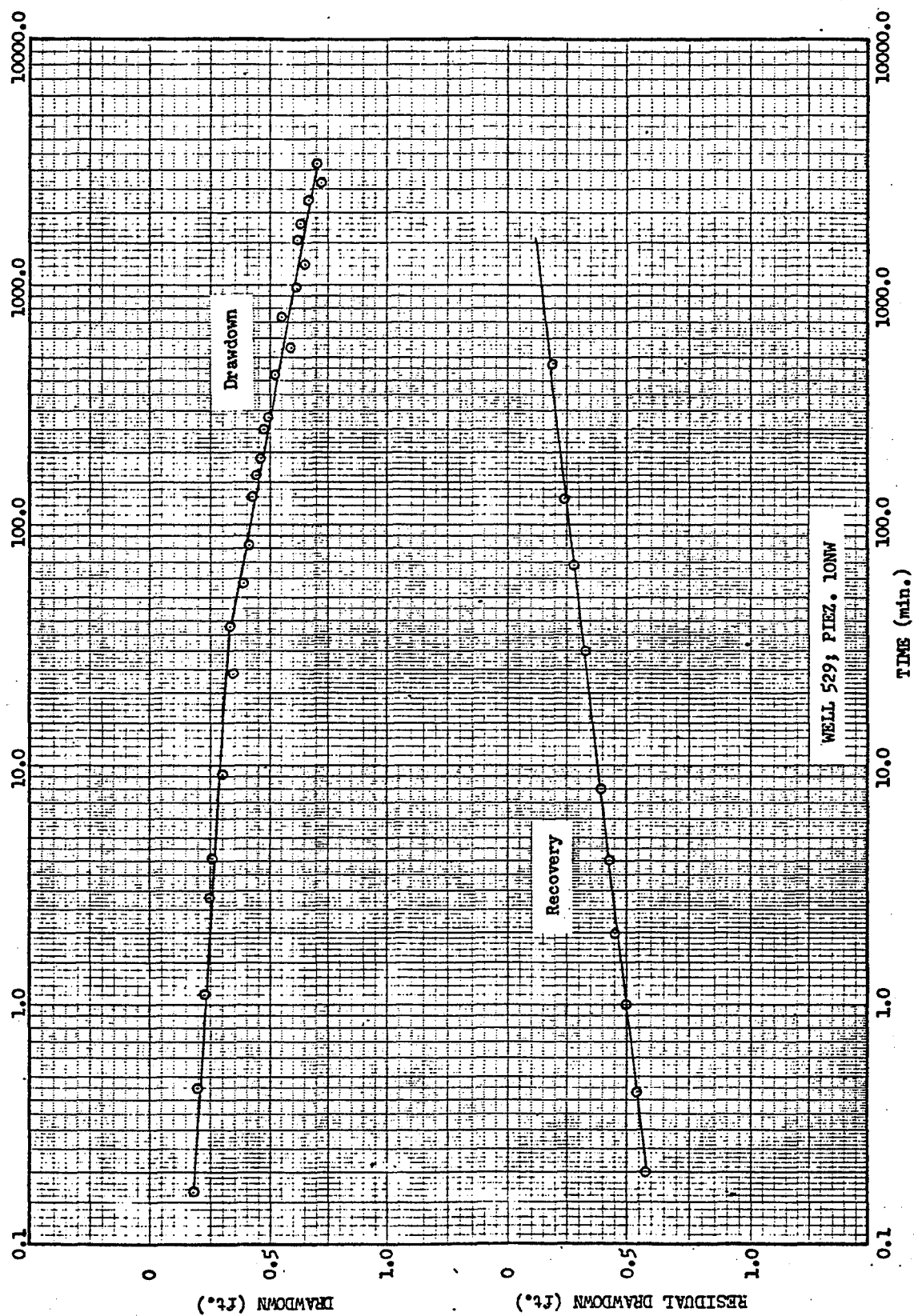


Figure 44. Drawdown and recovery versus time, Well 529; Piezometer 10NW

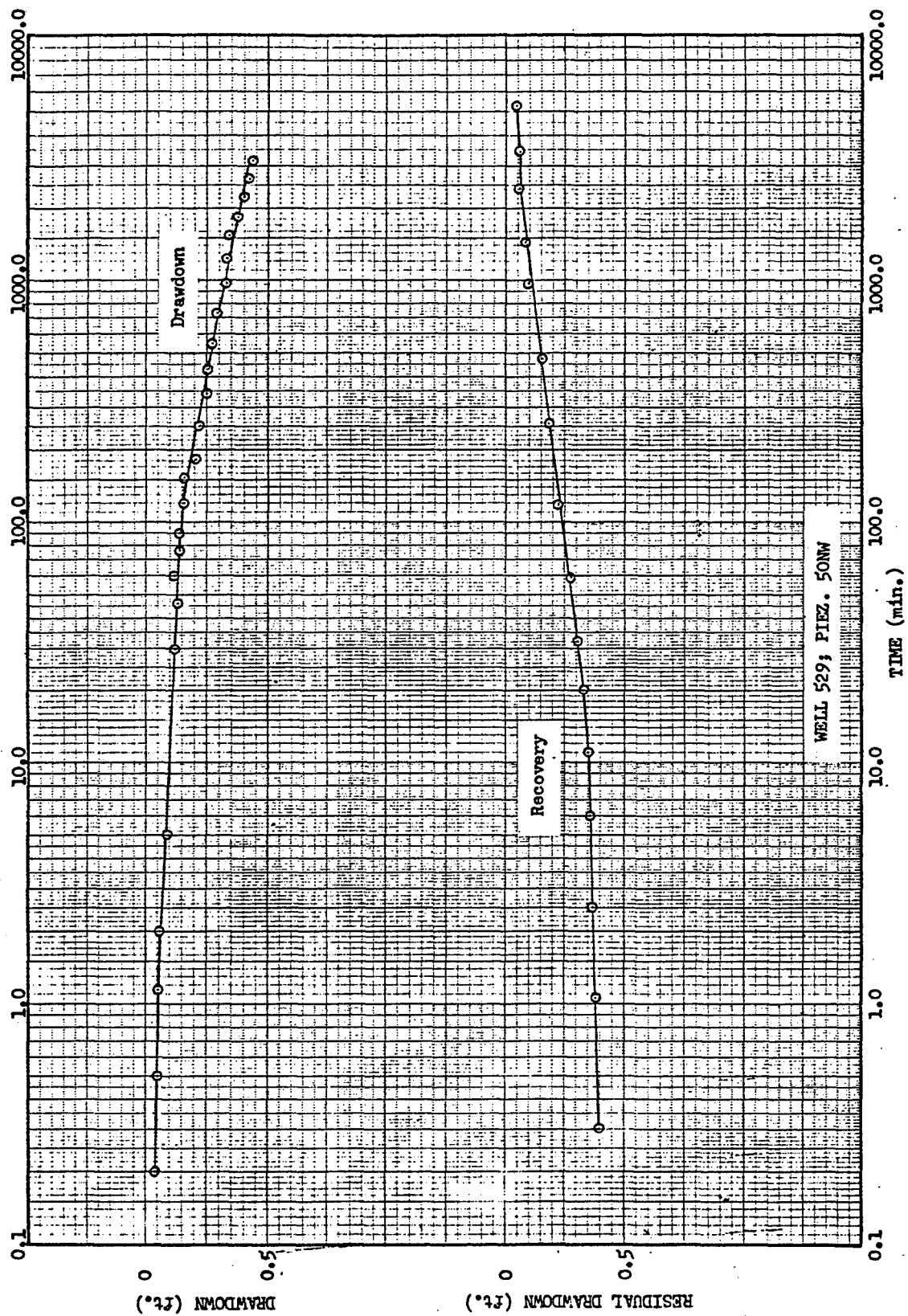


Figure 45. Drawdown and recovery versus time, Well 529; Piezometer 50NW

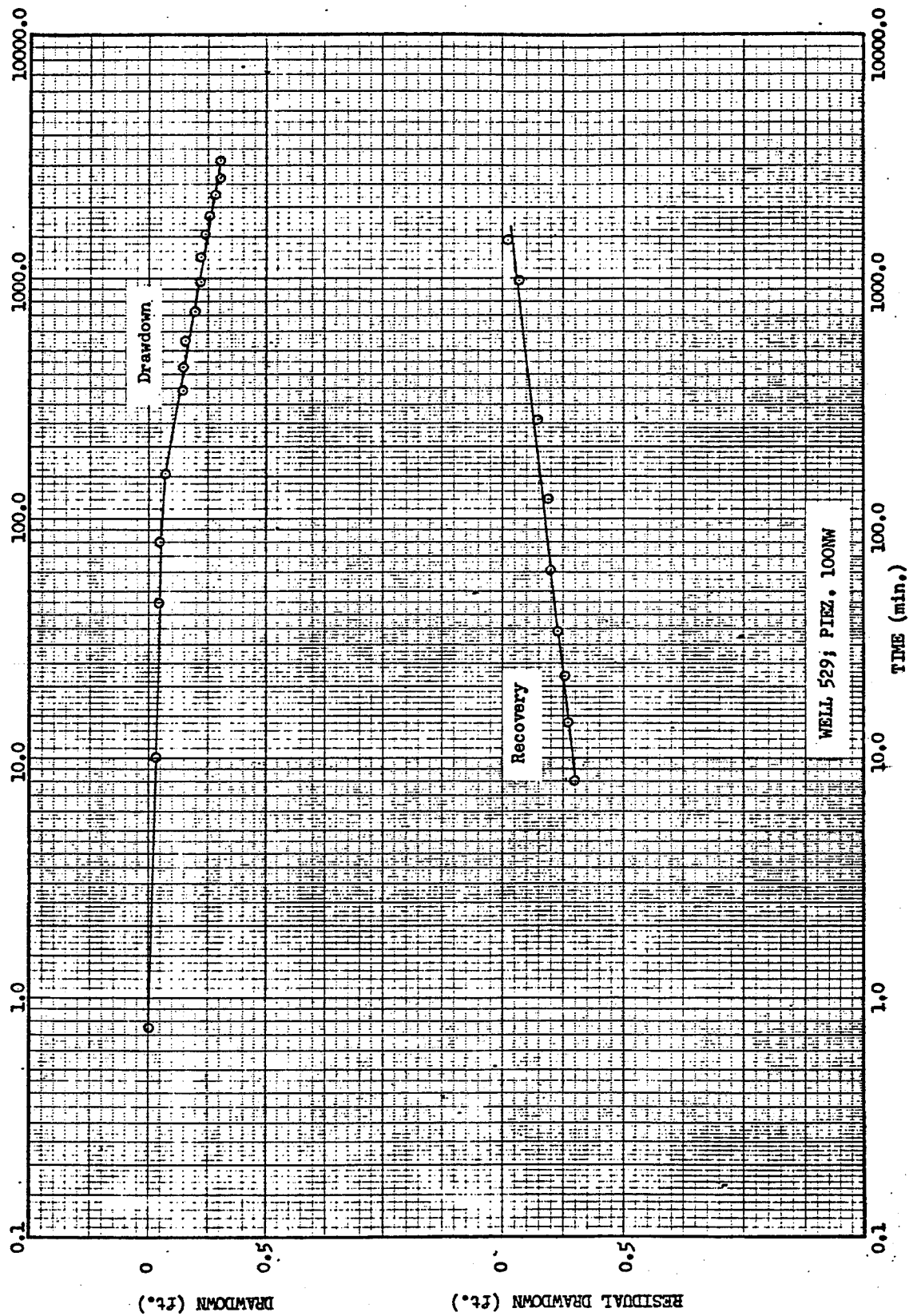


Figure 46. Drawdown and recovery versus time, Well 529; Piezometer 100NW

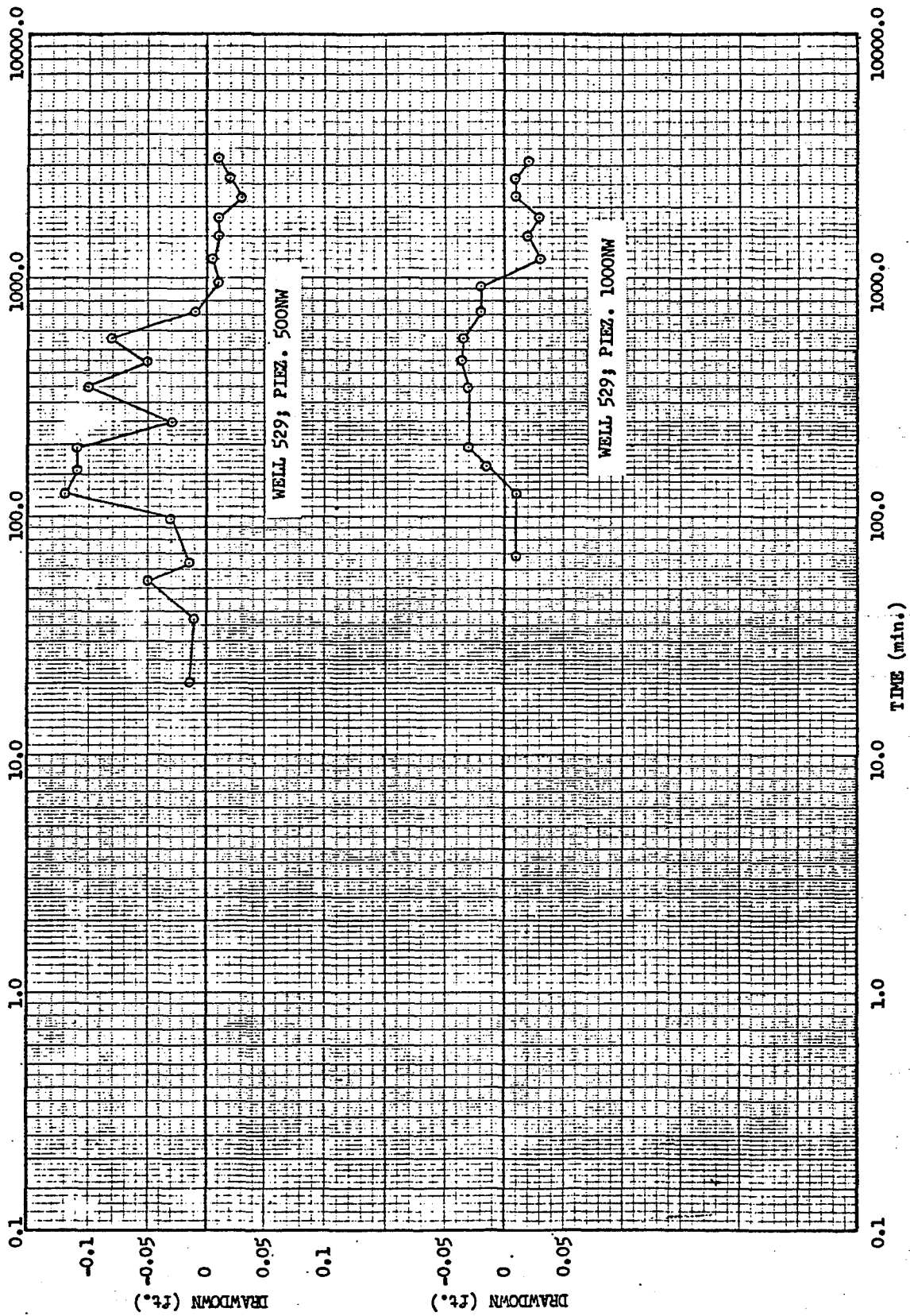


Figure 47. Drawdown versus time, Well 529; Piezometers 500NW and 1000NW

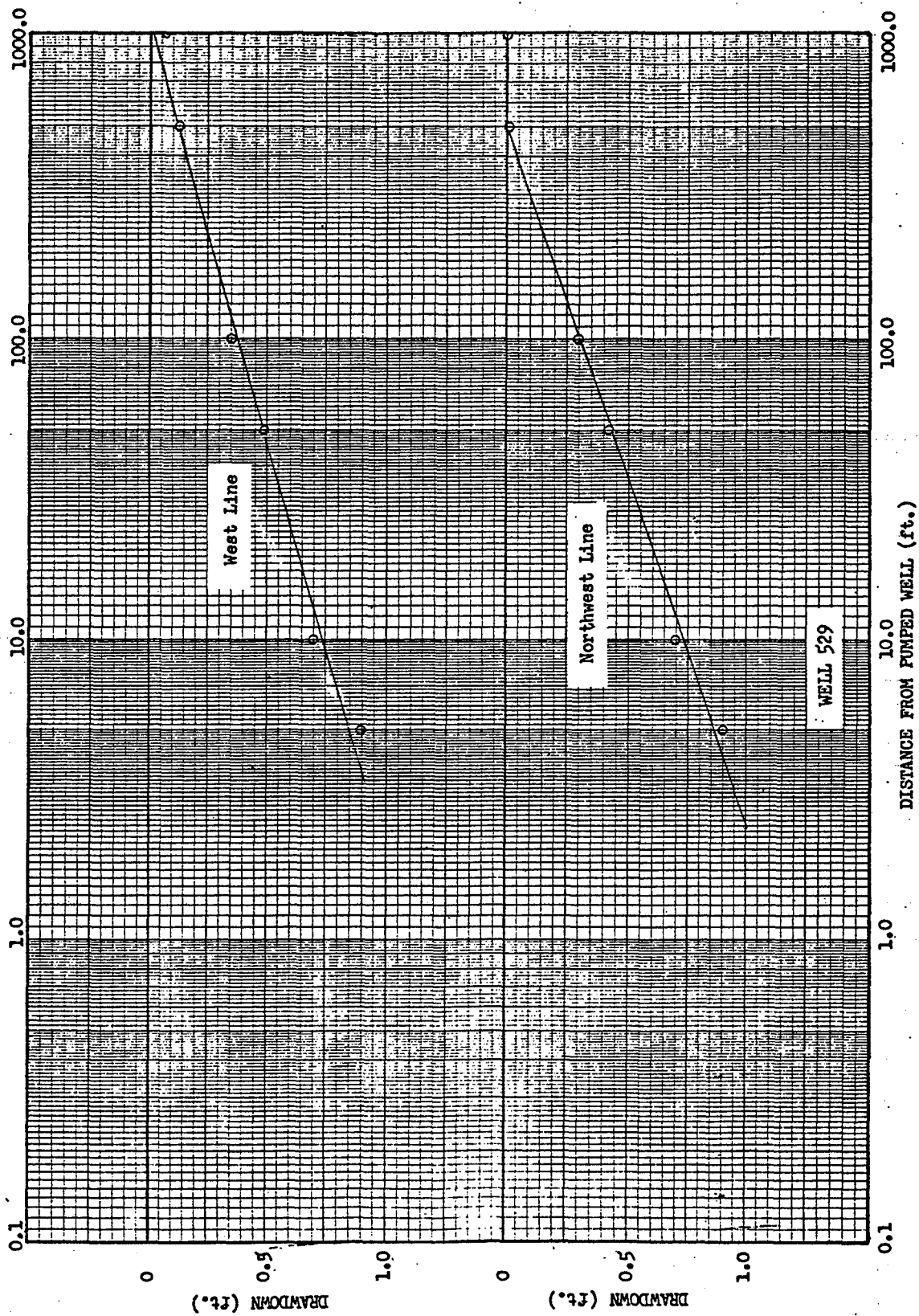


Figure 48. Drawdown versus distance from pumped well, Well 529

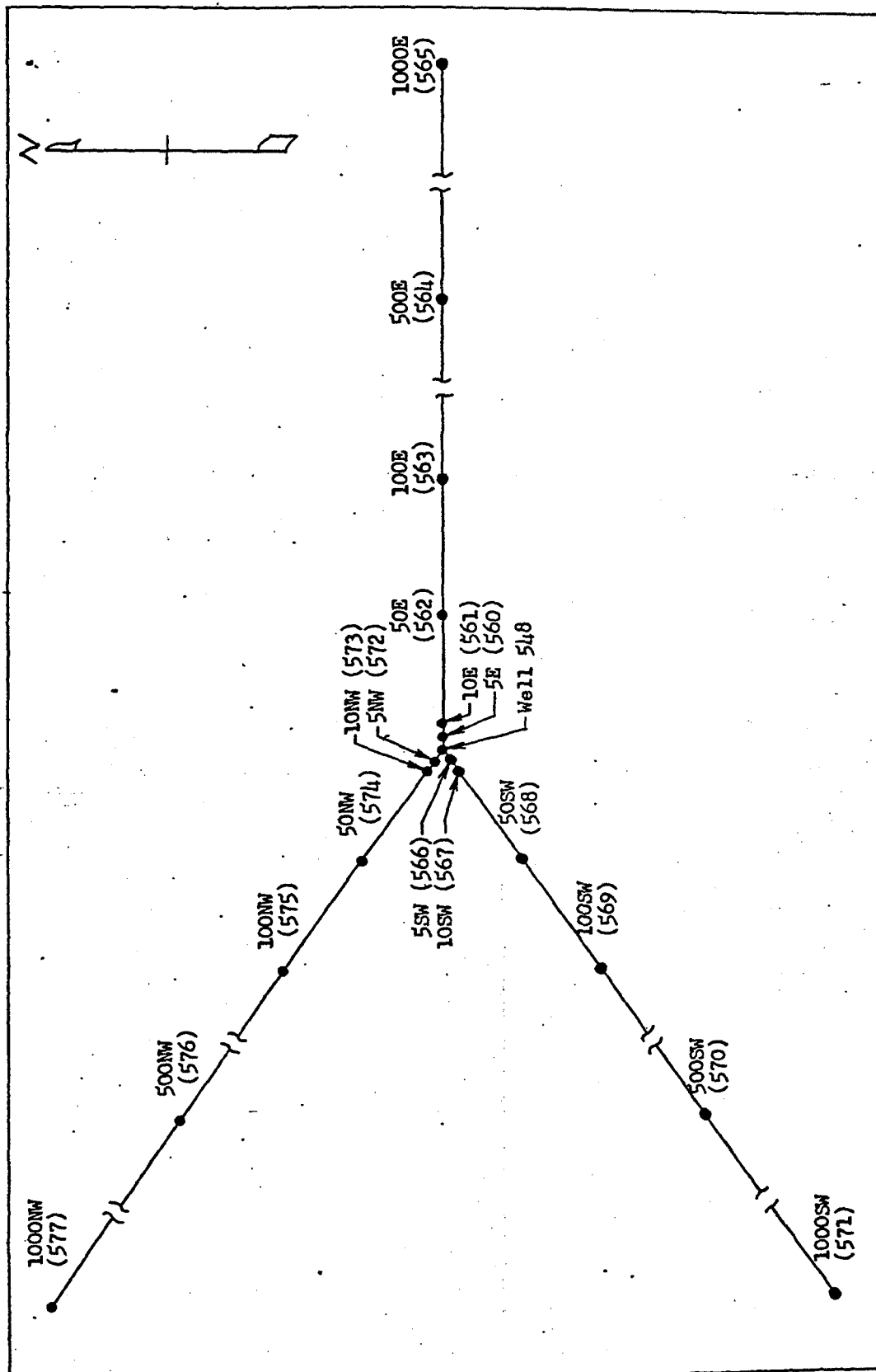


Figure 49. Piezometer layout for Test Well 548

Table 4: Well 548
(Pumping rate - 22 GPM)

Piezometer	Analysis Method	Transmissibility (gpd/ft)	Aquifer Thickness (ft)	Permeability (gpd/ft ²)
5 NW	Theis, Jacob, Chow and Theis Recovery	10,100-11,900	9.0	1,120-1,320
10 NW	Theis, Jacob, Chow and Theis Recovery	11,620-12,520	9.0	1,190-1,390
50 NW	Theis, Jacob, Chow and Theis Recovery	13,600-15,280	9.4	1,450-1,620
100 NW	Theis, Jacob, Chow and Theis Recovery	12,200-16,600	9.8	1,240-1,690
5 SW	Theis, Jacob, Chow and Theis Recovery	11,500-13,800	9.0	1,280-1,530
10 SW	Theis, Jacob, Chow and Theis Recovery	12,600-13,700	9.0	1,400-1,520
50 SW	Theis, Jacob, Chow and Theis Recovery	18,890-19,690	8.4	2,250-2,340
100 SW	Theis, Jacob, Chow and Theis Recovery	19,230-22,780	7.8	2,460-2,920
5 E	Theis, Jacob, Chow and Theis Recovery	10,700-13,500	9.0	1,190-1,500
10 E	Theis, Jacob, Chow and Theis Recovery	12,140-14,500	9.0	1,350-1,610
50 E	Theis, Jacob, Chow and Theis Recovery	15,500-21,400	9.5	1,630-2,250
100 E	Theis, Jacob, Chow and Theis Recovery	17,710-22,780	10.0	1,770-2,280
Well	Theis Recovery	10,100	9.0	1,120
Northwest line	Jacob (Drawdown vs log distance)			
0-50		12,910	10.0	1,290
50-1000		14,520	10.5	1,380
Southwest line	Jacob (Drawdown vs log distance)			
0-50		11,620	8.8	1,320
50-1000		17,870	9.0	1,980
East line	Jacob (Drawdown vs log distance)			
0-50		13,351	9.2	1,451
50-1000		17,080	10.0	1,710

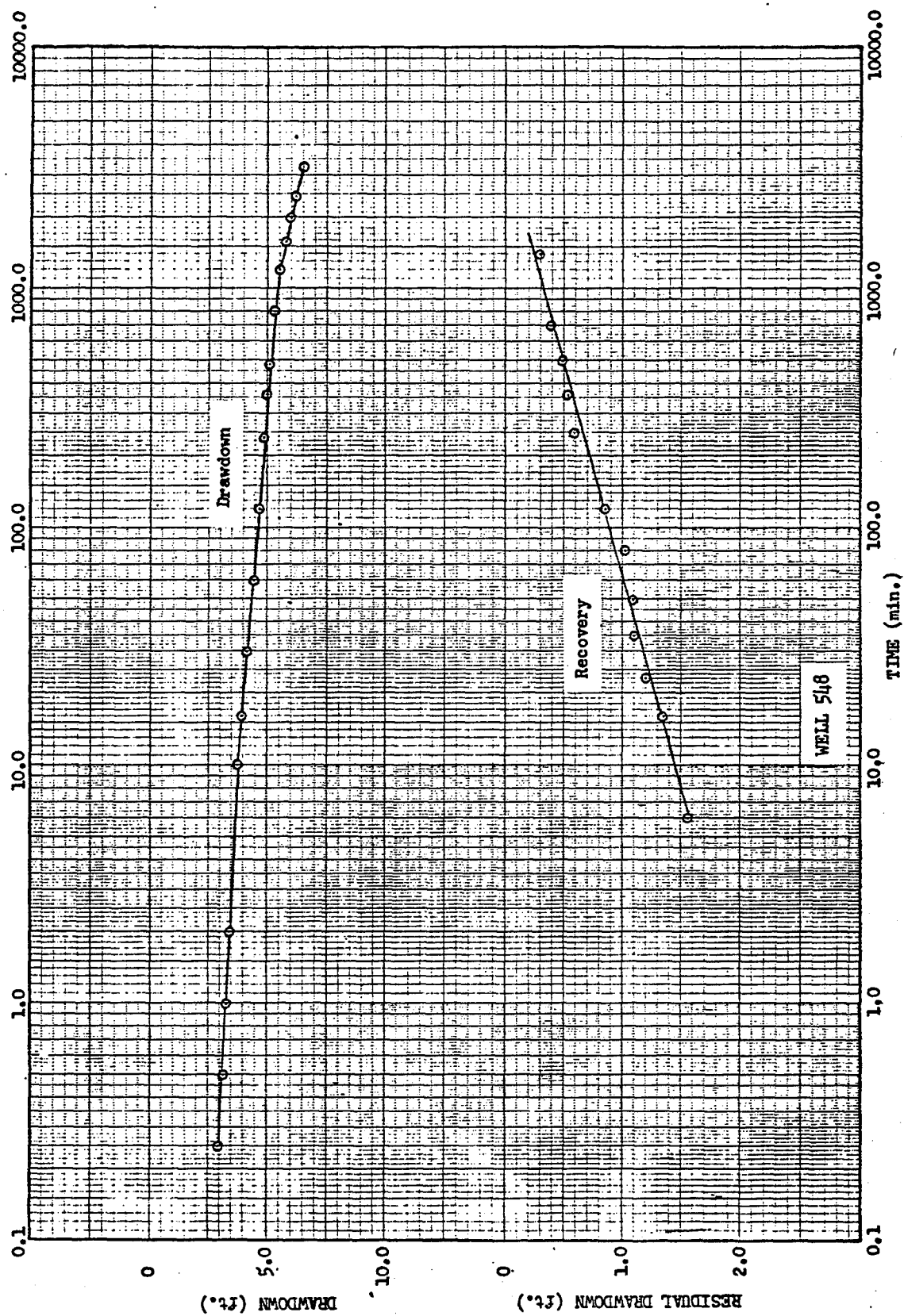


Figure 50. Drawdown and recovery versus time, Well 548

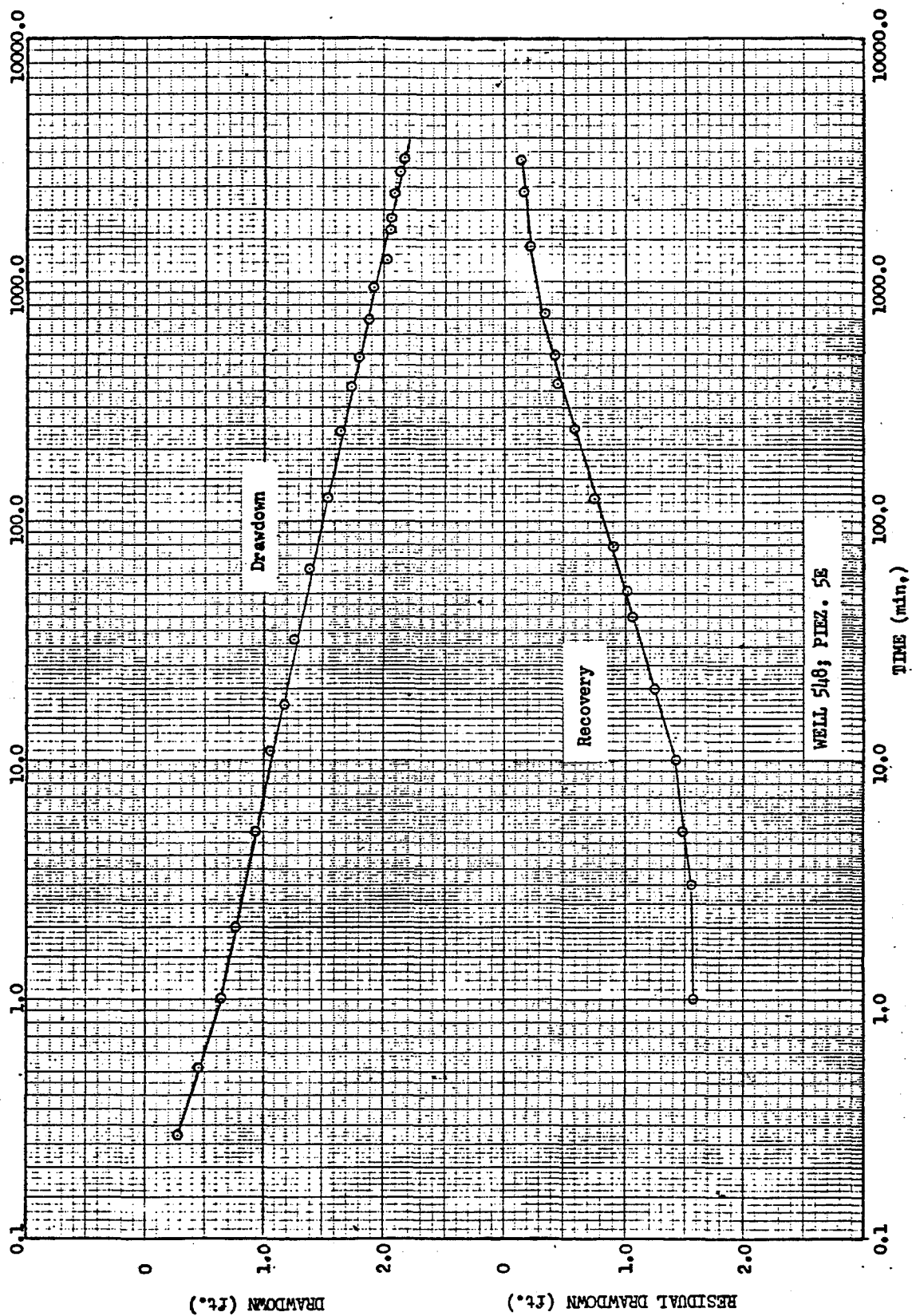


Figure 51. Drawdown and recovery versus time, Well 548; Piezometer 5E

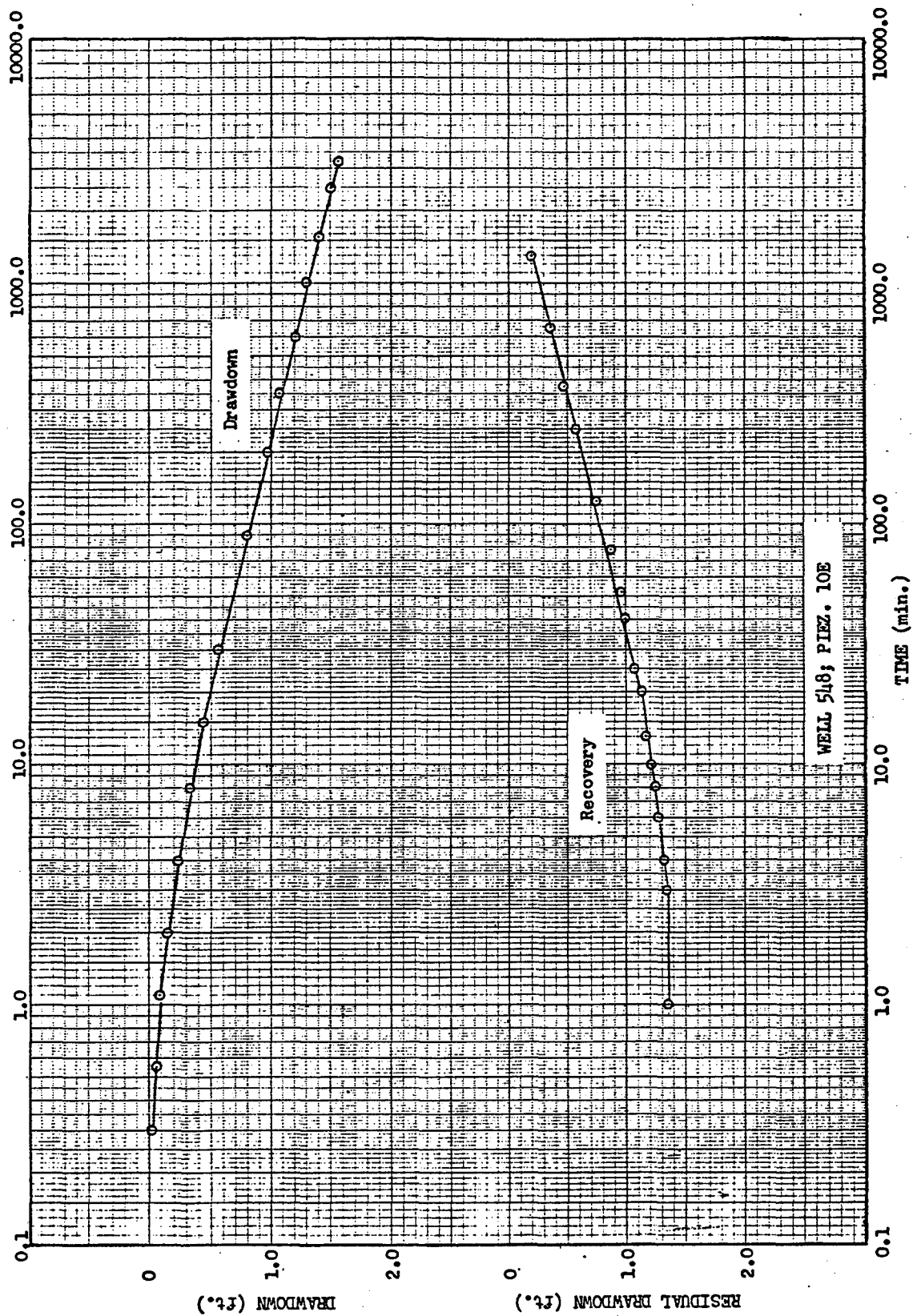


Figure 52. Drawdown and recovery versus time, Well 548; Piezometer 10E

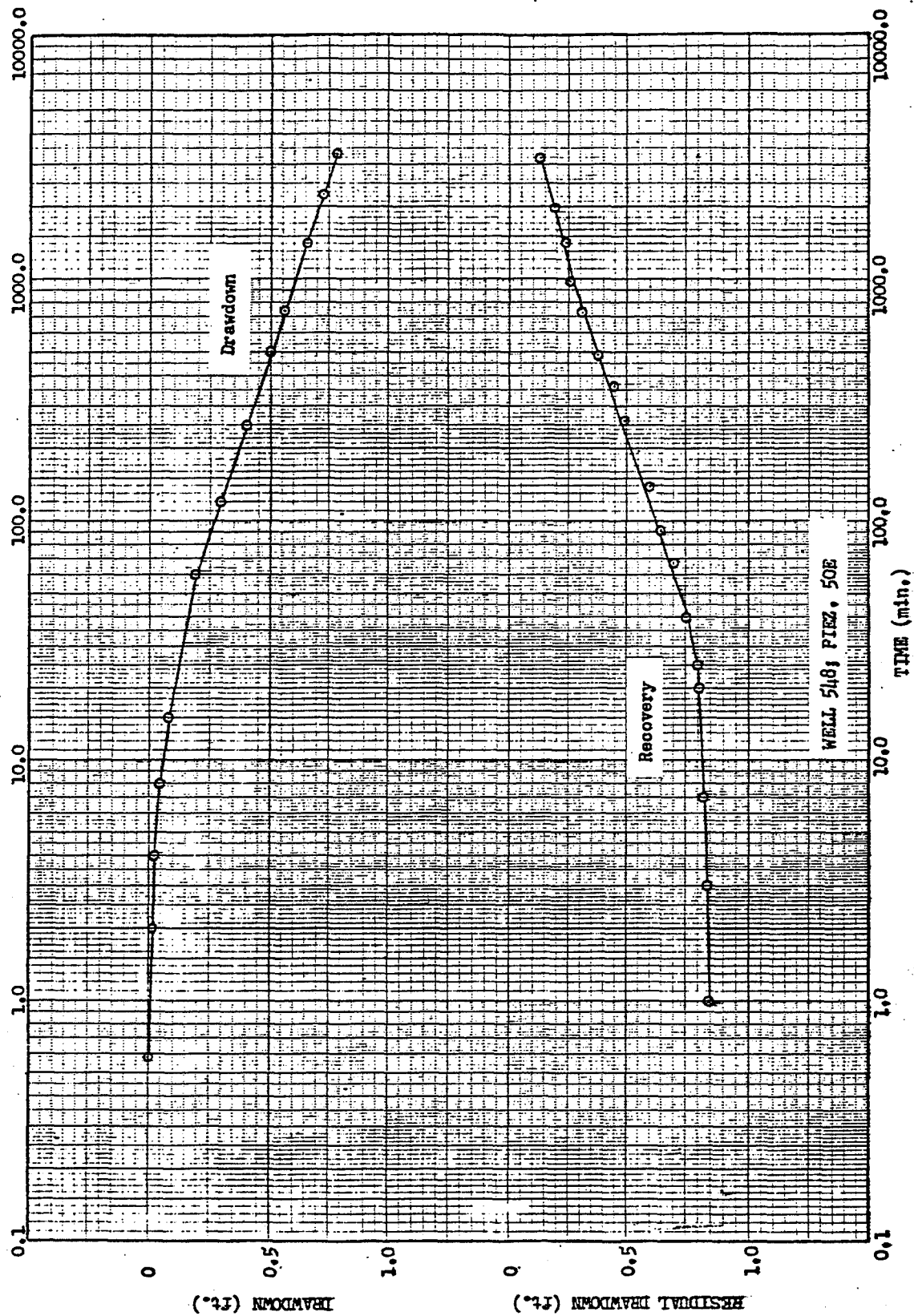


Figure 53. Drawdown and recovery versus time, Well 548; Piezometer 50E

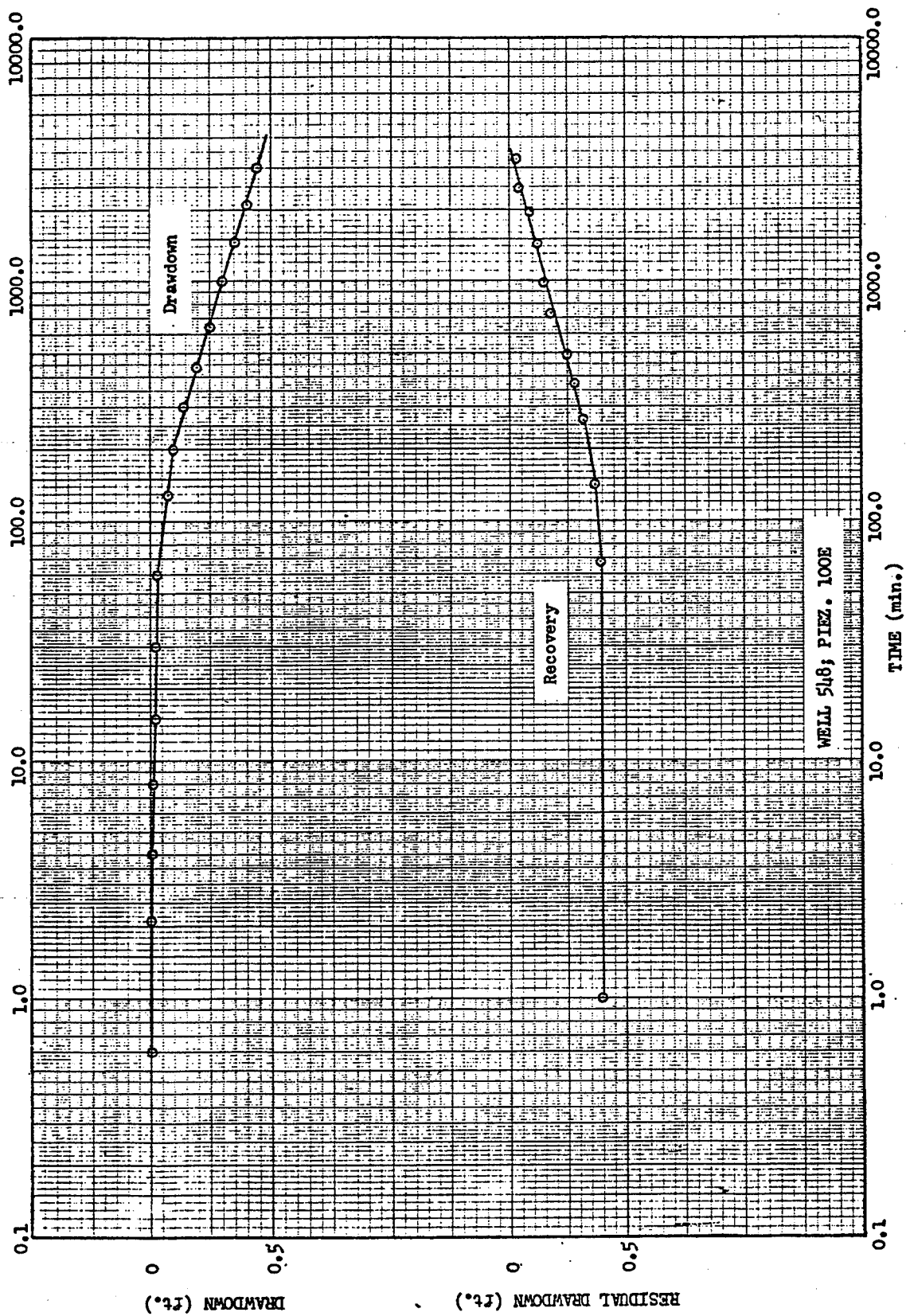


Figure 54. Drawdown and recovery versus time, Well 548; Piezometer 100E

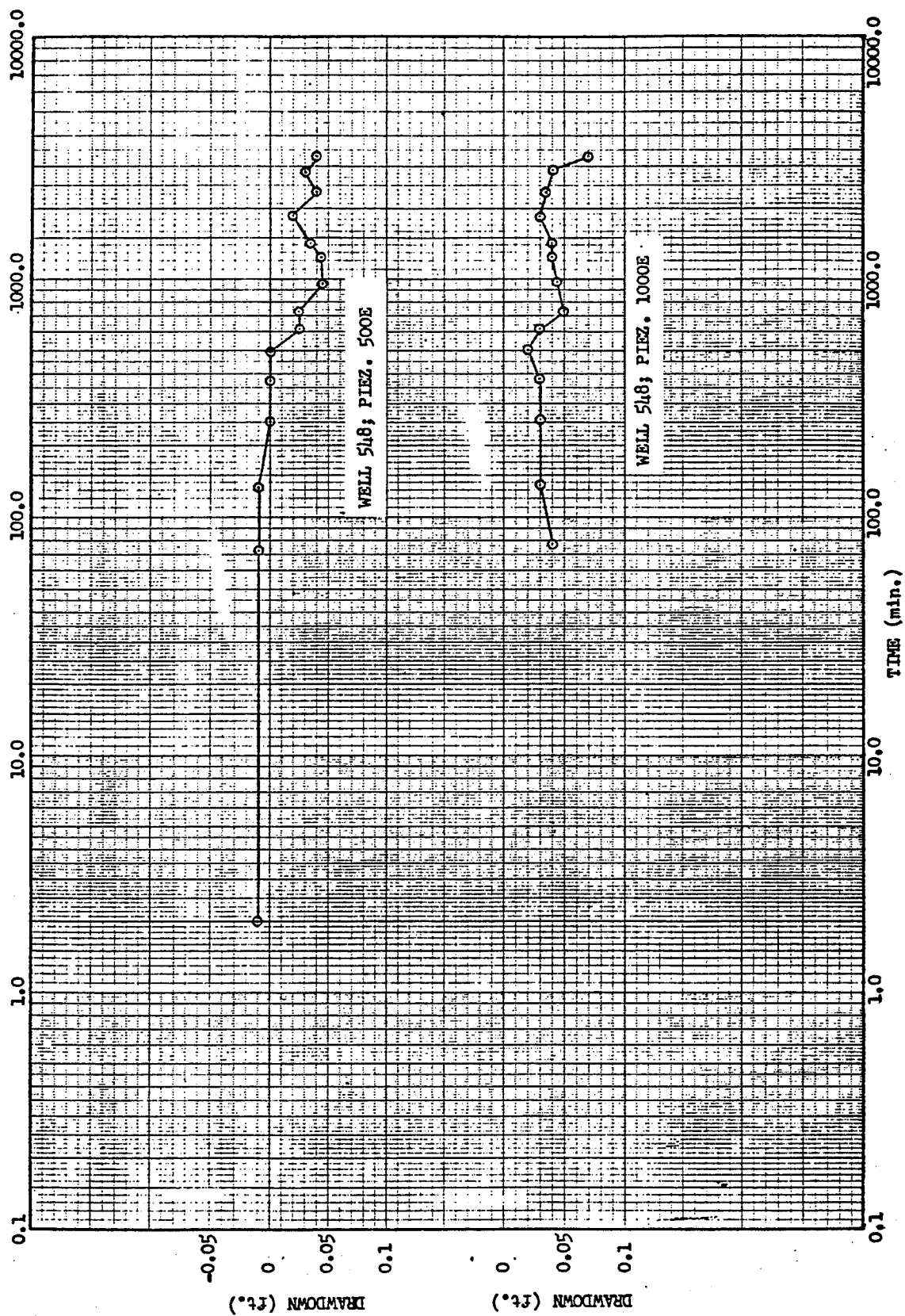


Figure 55. Drawdown versus time, Well 548; Piezometers 500E and 1000E

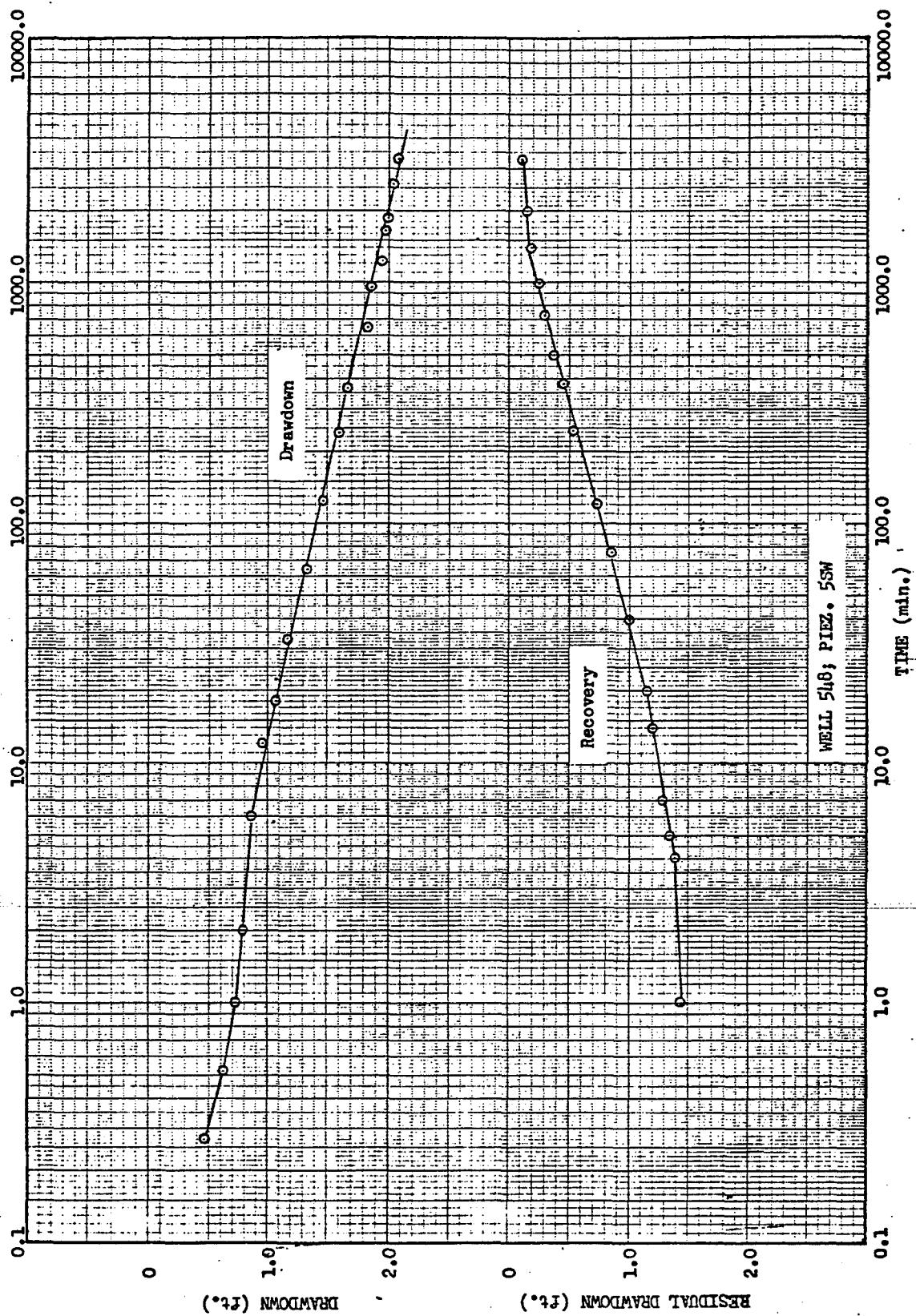


Figure 56. Drawdown and recovery versus time, Well 548; Piezometer 5SW

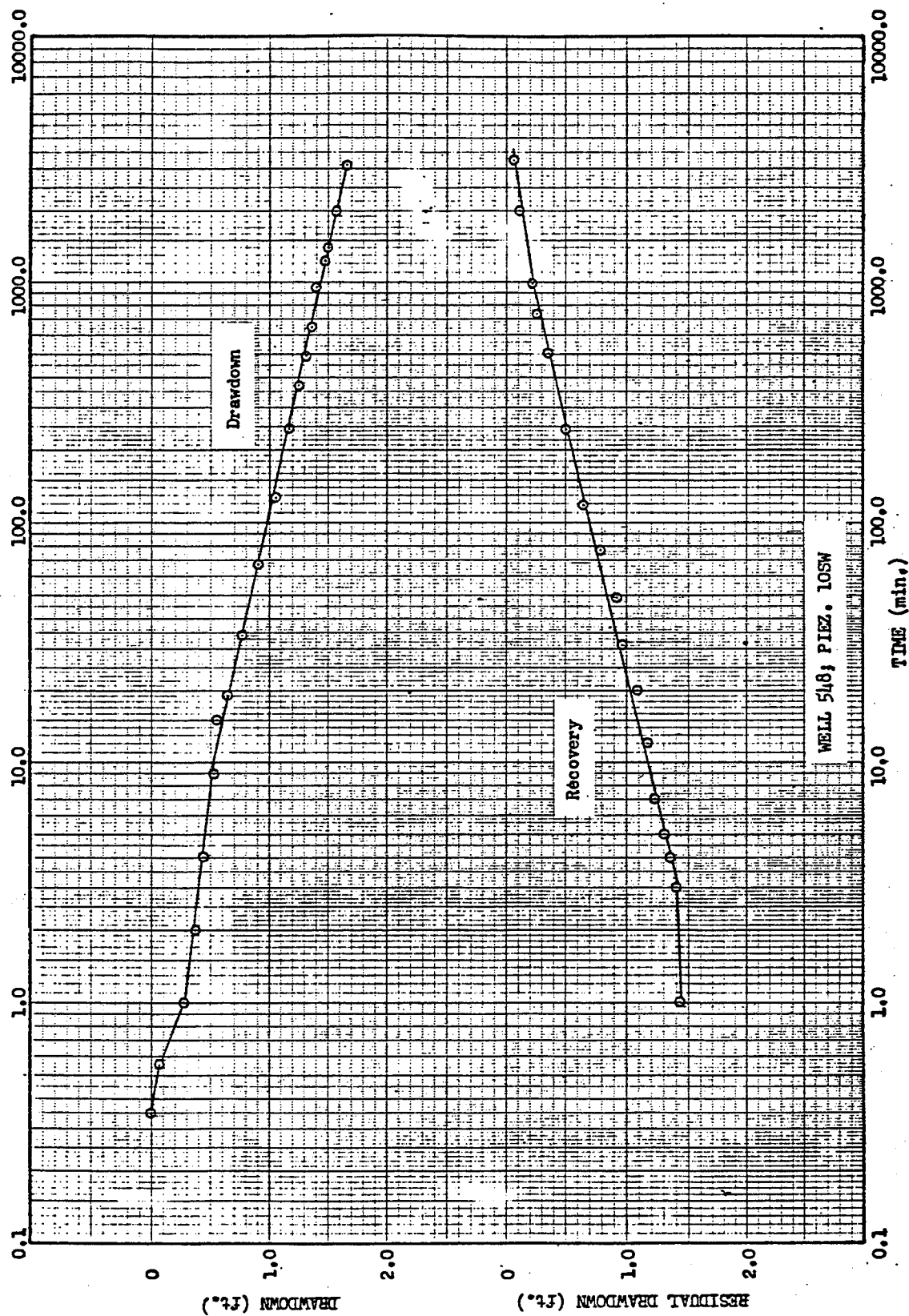


Figure 57. Drawdown and recovery versus time, Well 548; Piezometer LOSW

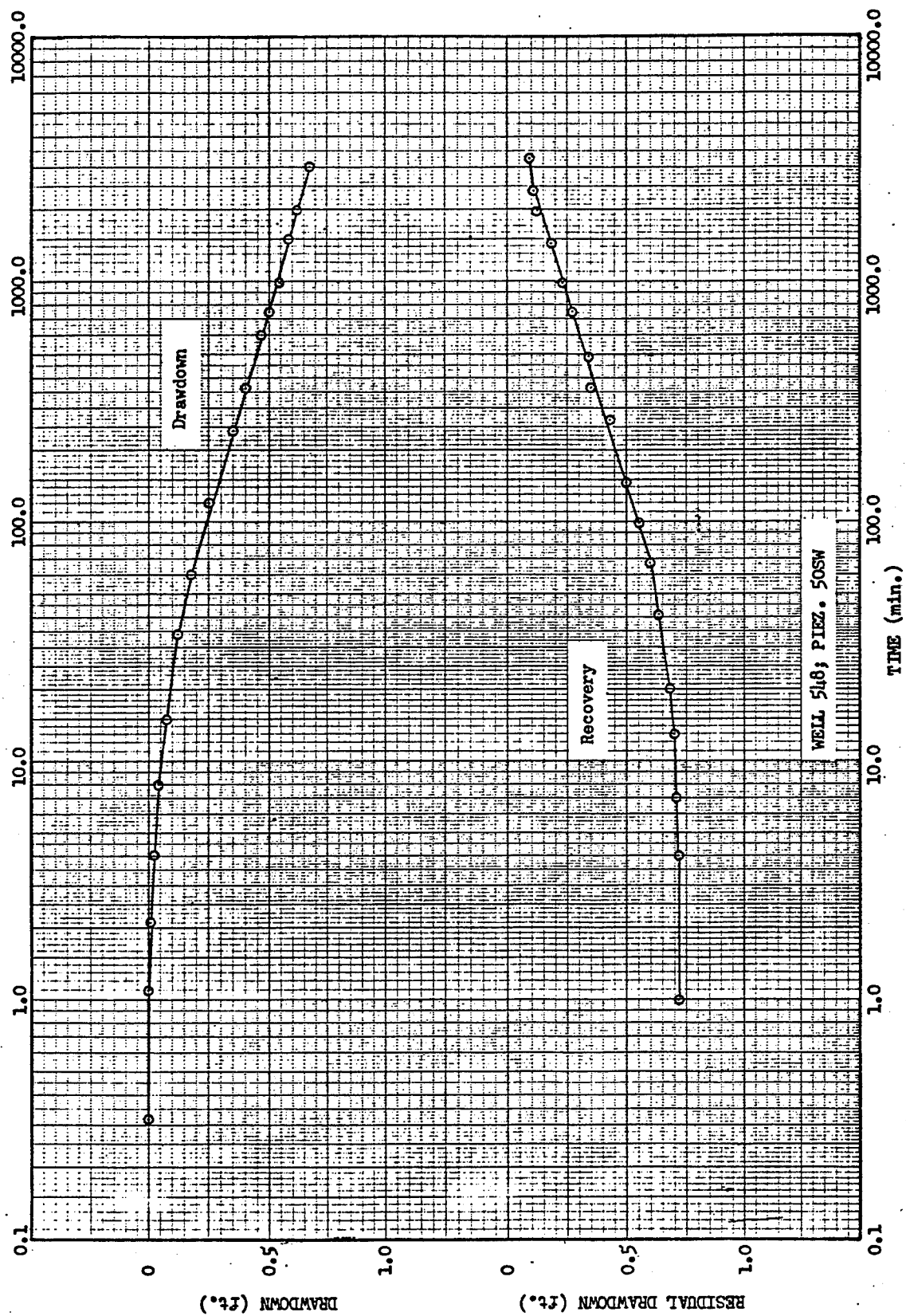


Figure 58. Drawdown and recovery versus time, Well 548; Piezometer 50SW

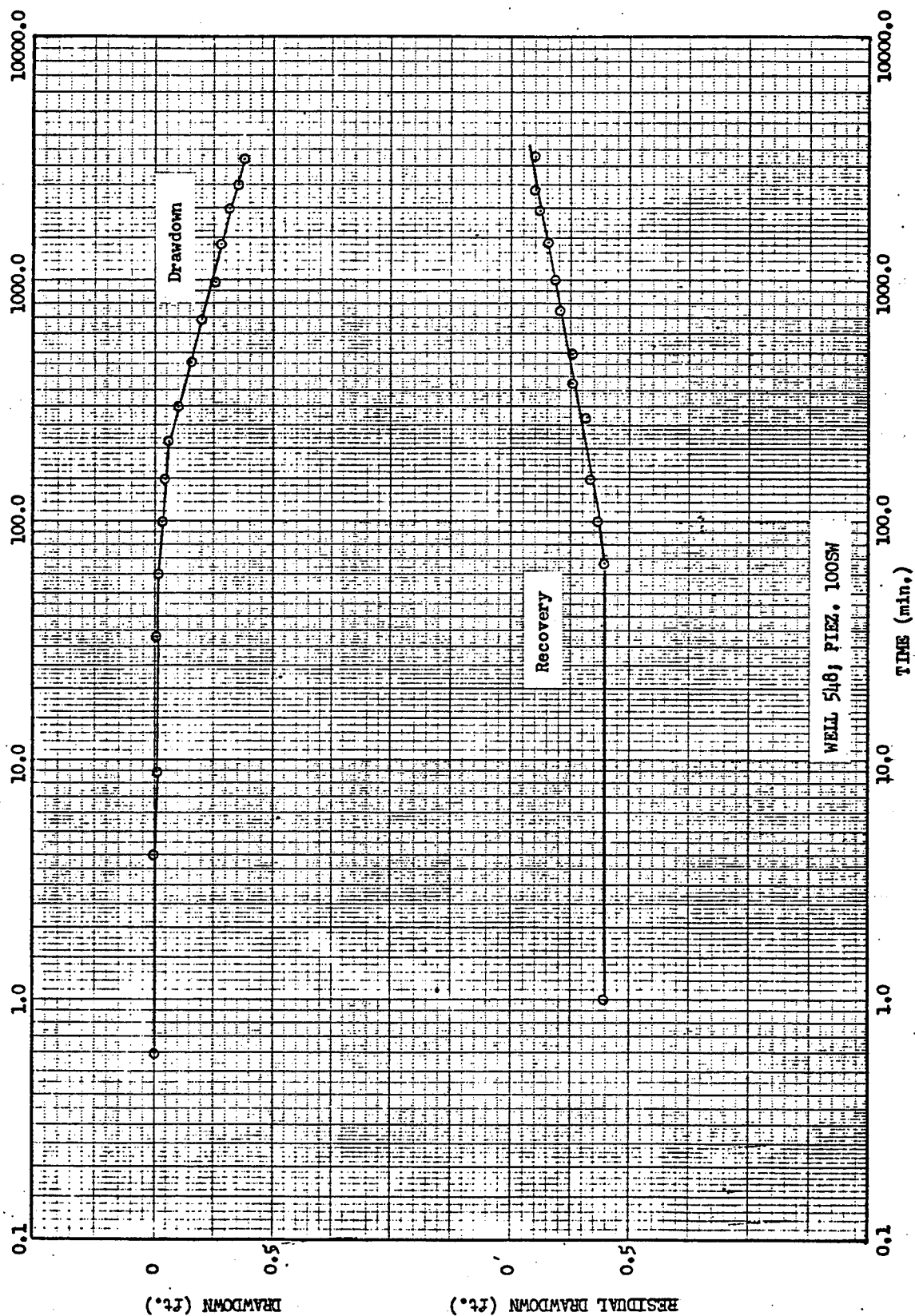


Figure 59. Drawdown and recovery versus time, Well 548; Piezometer 100SW

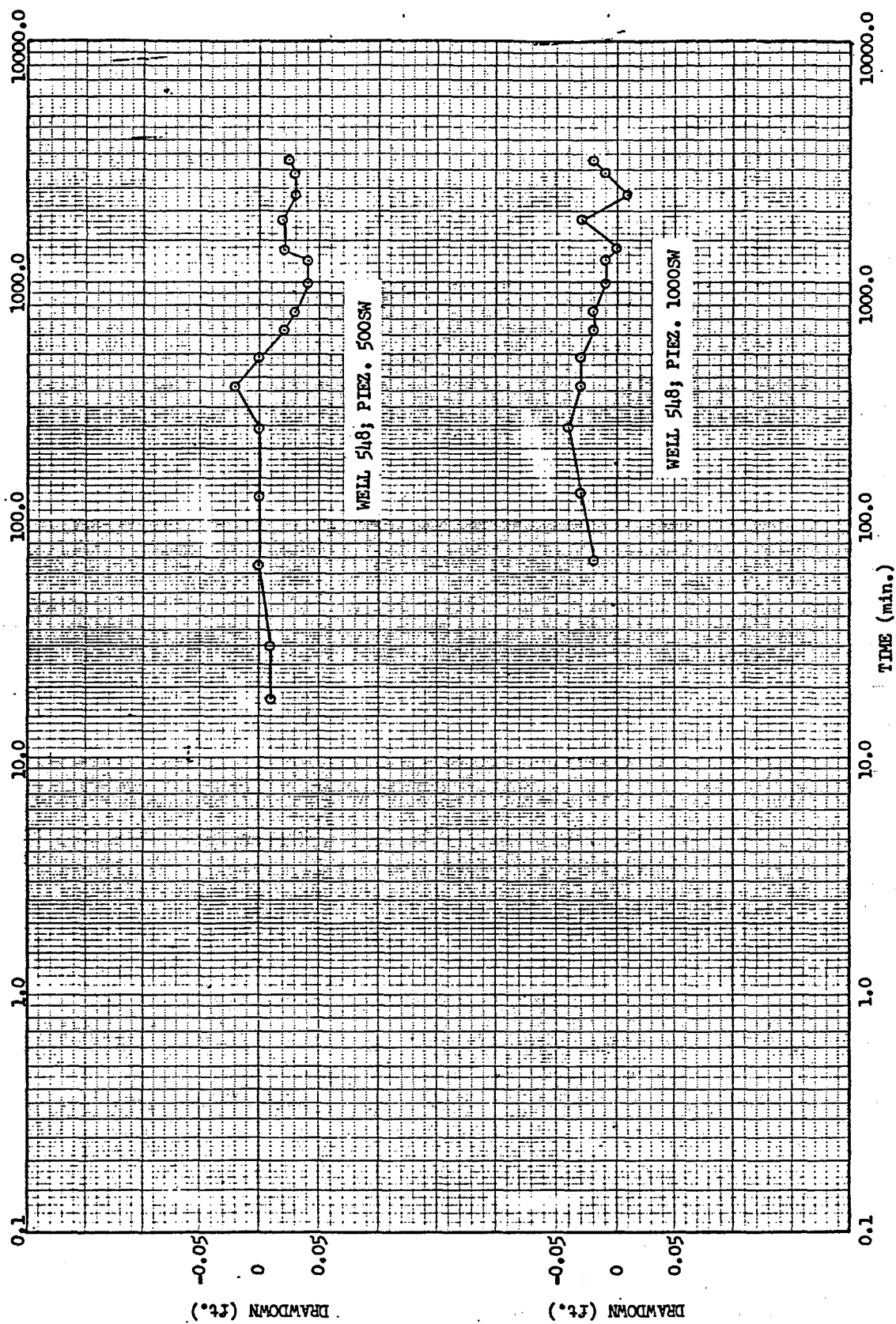


Figure 60. Drawdown versus time, Well 548; Piezometers 500SW and 1000SW

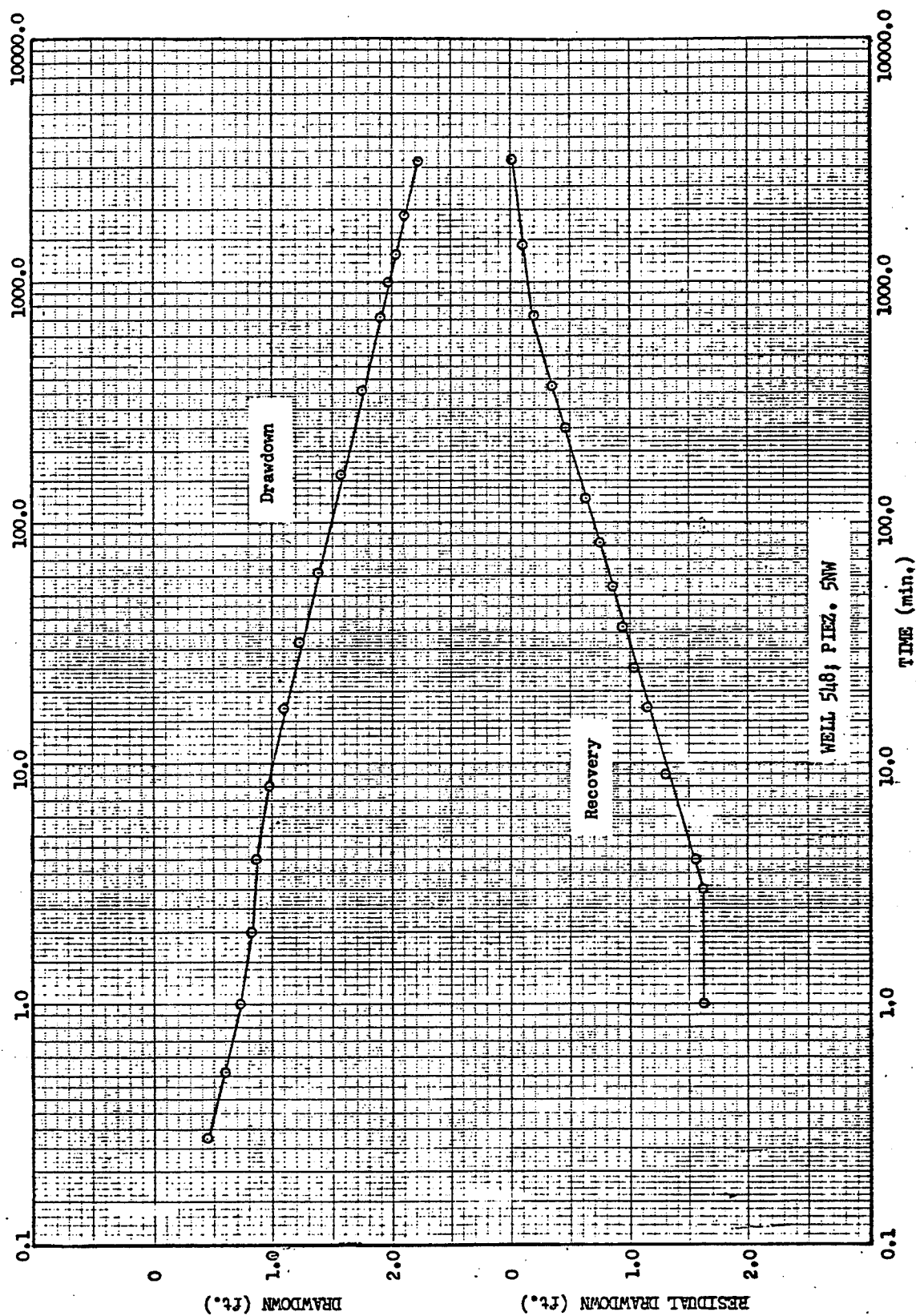


Figure 61. Drawdown and recovery versus time, Well 548; Piezometer 5NW

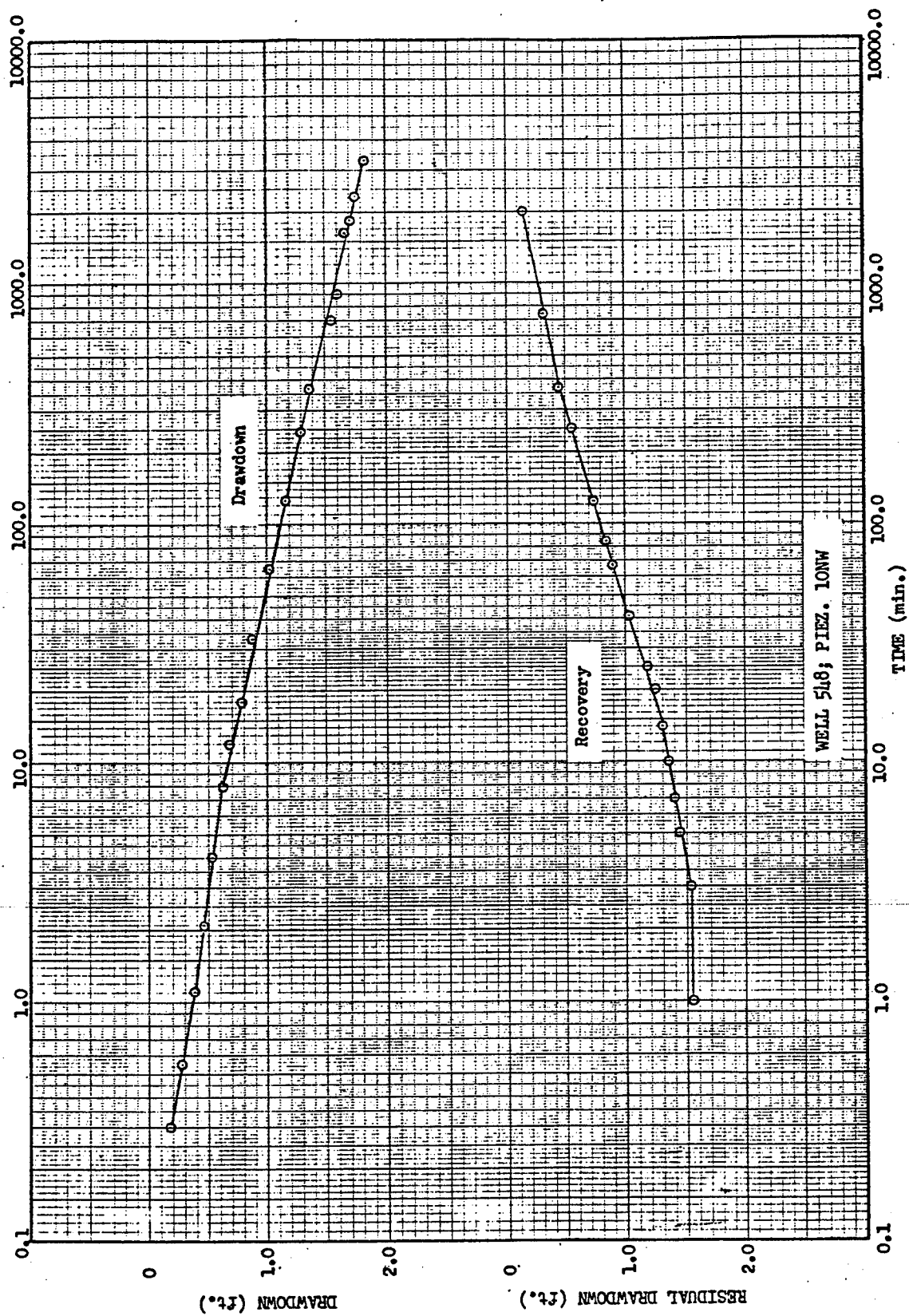


Figure 62. Drawdown and recovery versus time, Well 548; Piezometer 10NW

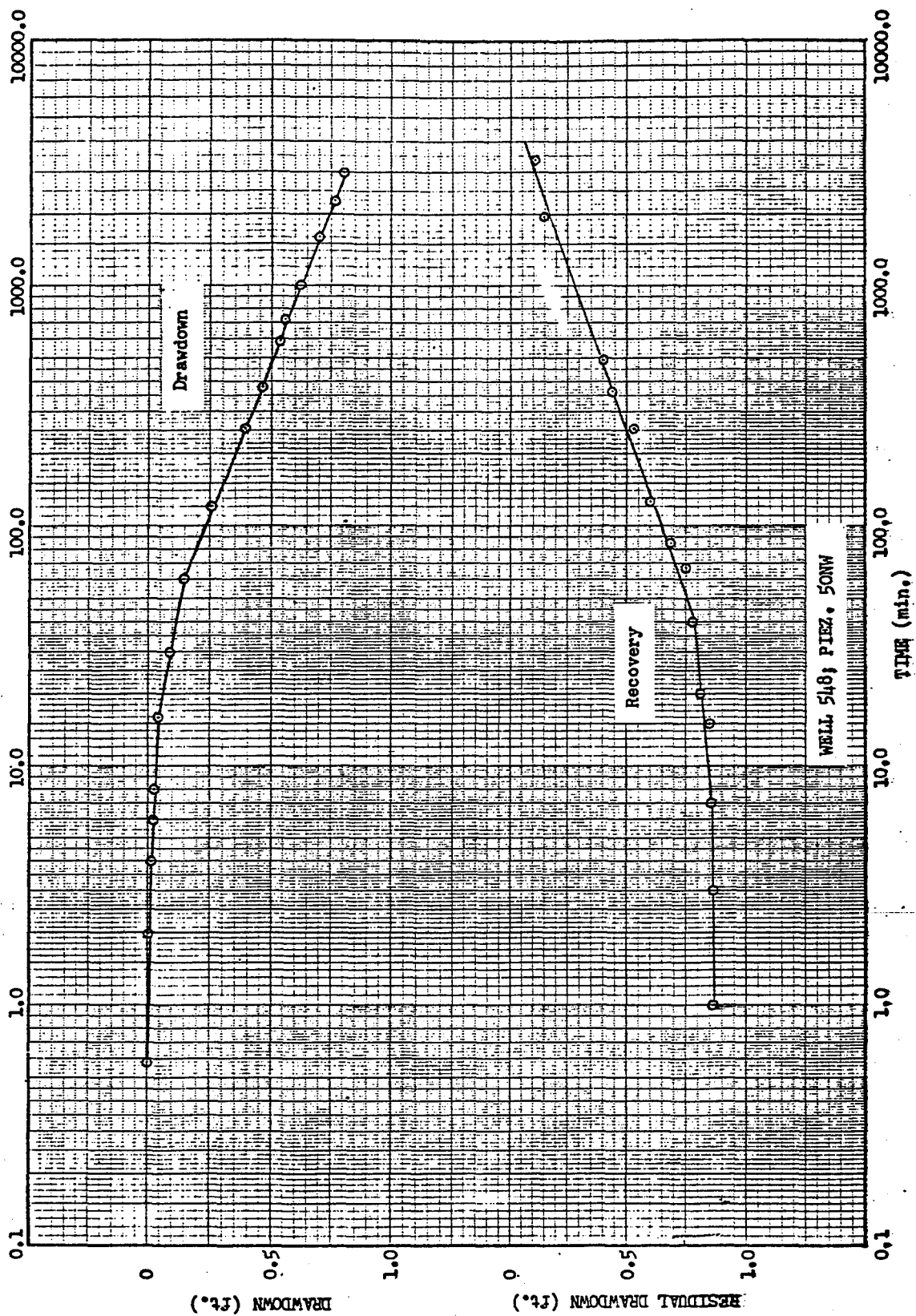


Figure 63. Drawdown and recovery versus time, Well 548; Piezometer 50NW

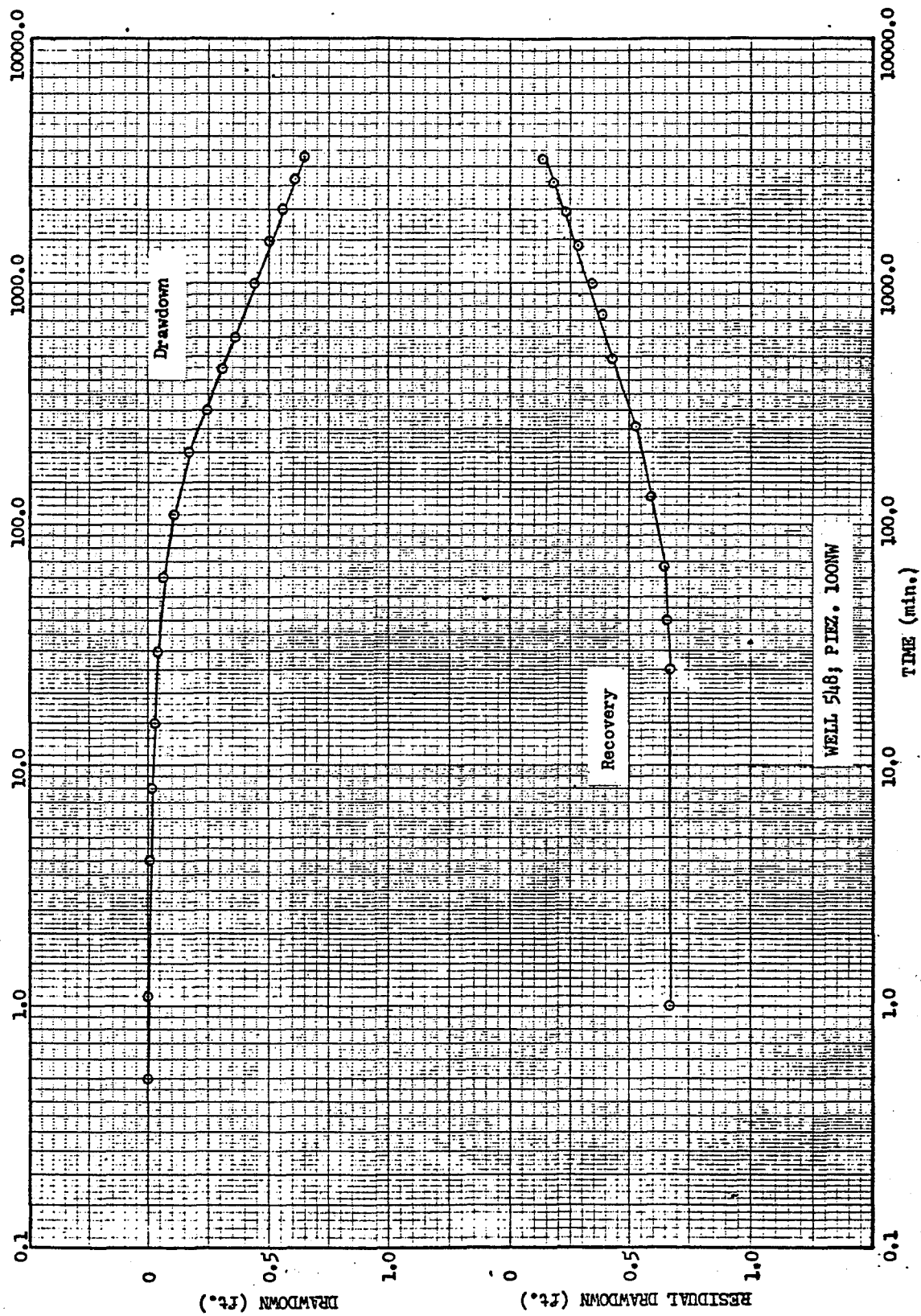


Figure 64. Drawdown and recovery versus time, Well 548; Piezometer 100NW

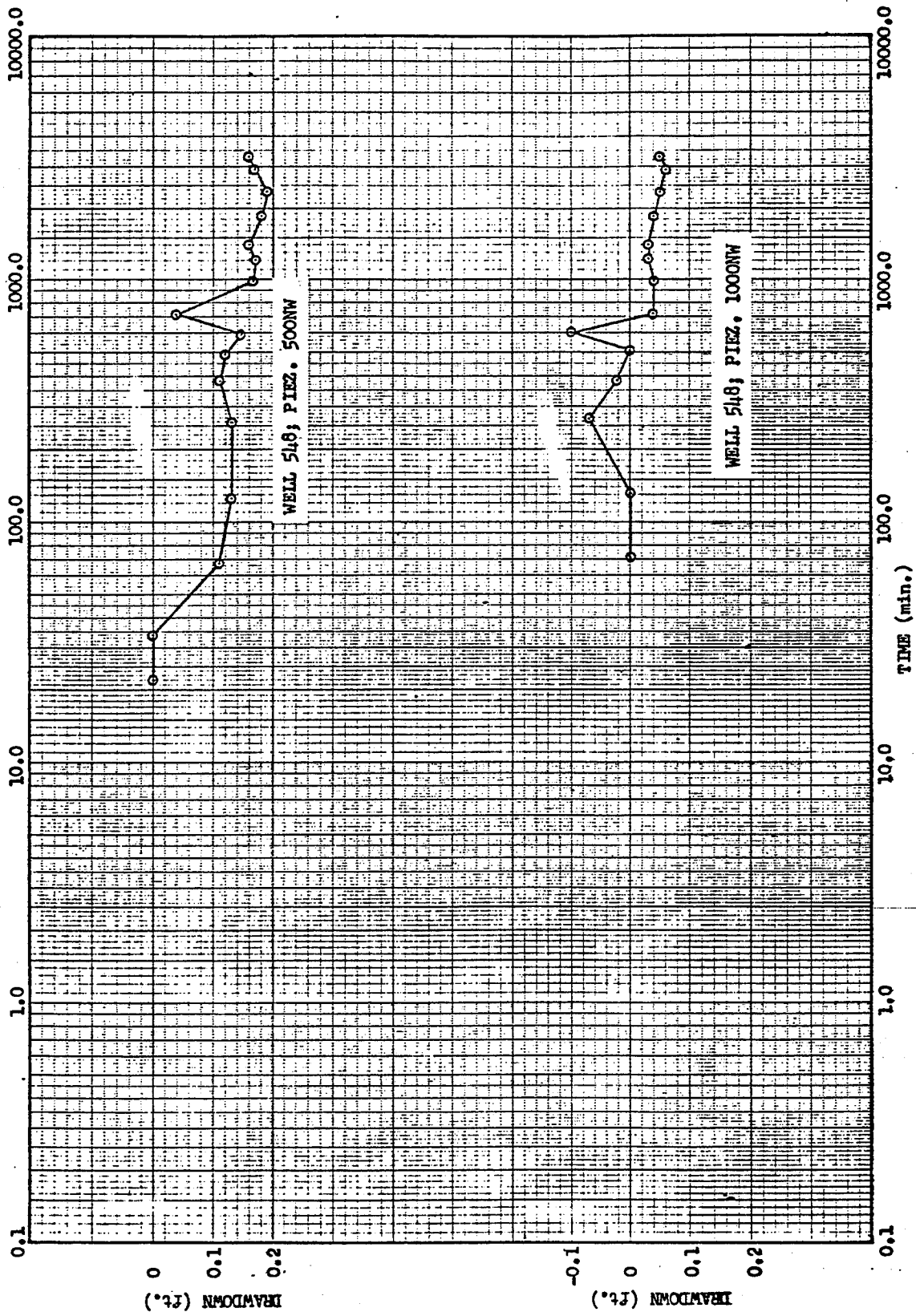


Figure 65. Drawdown versus time, Well 548; Piezometers 500NW and 1000NW

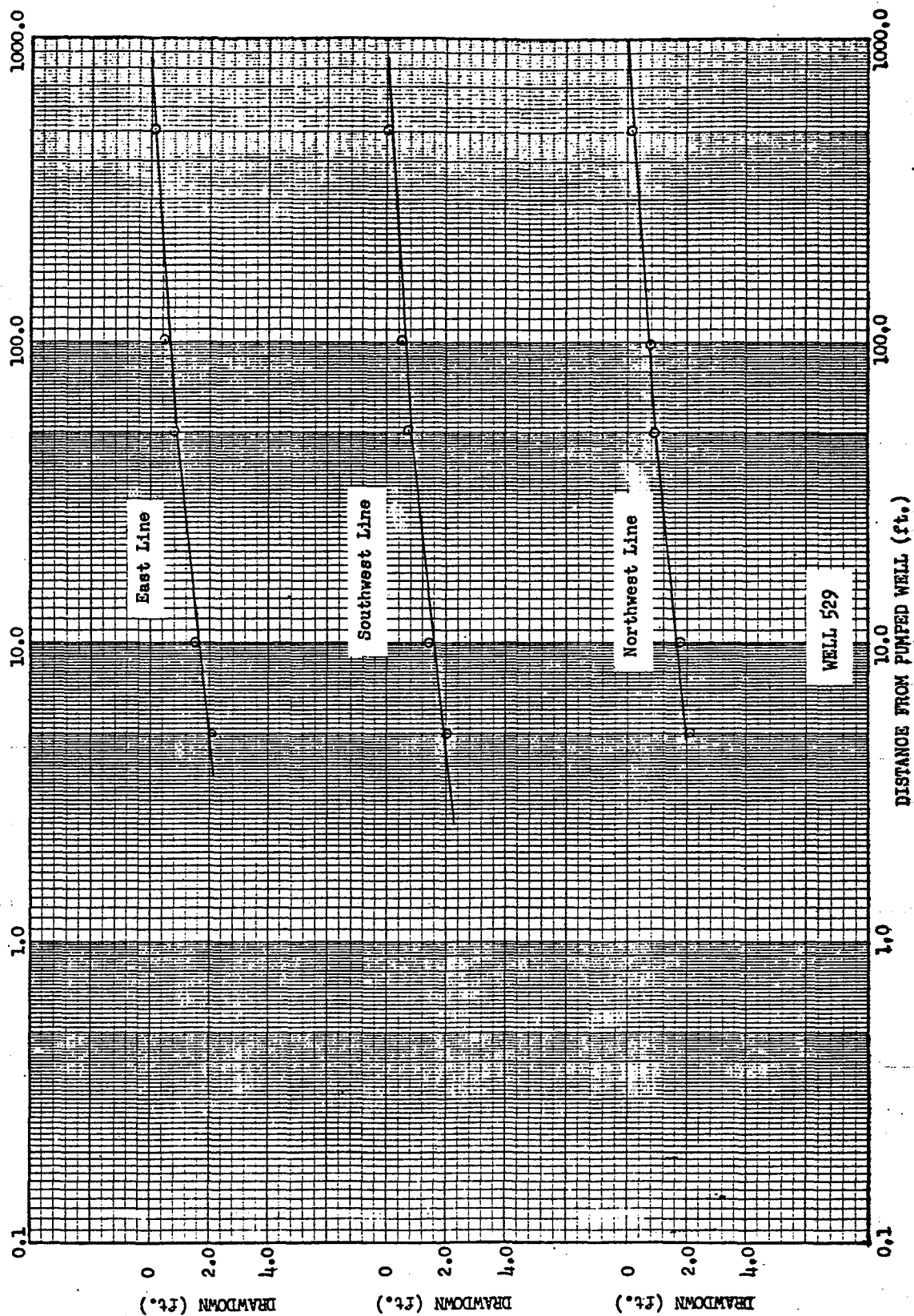


Figure 66. Drawdown versus distance from pumped well, Well 548

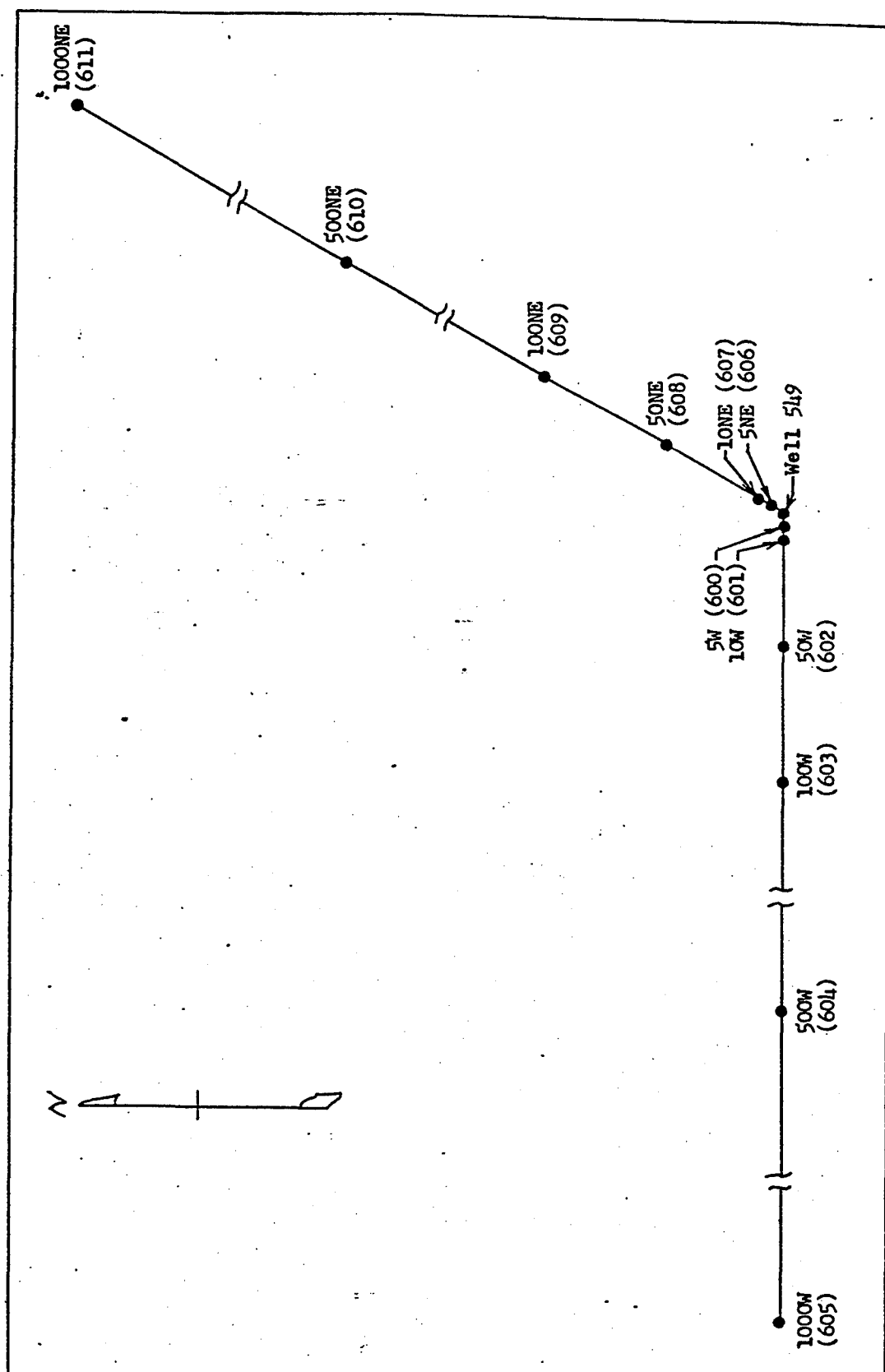


Figure 67. Piezometer layout for Test Well 549

Table 5: Well 549
(Pumping rate - 5 GPM)

<u>Piezometer</u>	<u>Analysis Method</u>	<u>Transmissibility (gpd/ft)</u>	<u>Aquifer Thickness (ft)</u>	<u>Permeability (gpd/ft²)</u>
5 W	Theis, Jacob, Chow Theis Recovery	1,800- 7,150	9.0	200- 794
10 W	Theis, Jacob, Chow Theis Recovery	1,450- 7,300	9.0	161- 811
50 W	Theis, Jacob, Chow Theis Recovery	5,800-15,000	9.0	640-1,670
100 W	Theis, Jacob, Chow Theis Recovery	8,800-20,600	10.0	980-2,060
5 NE	Theis, Jacob, Chow Theis Recovery	1,400- 8,015	9.0	160- 900
10 NE	Theis, Jacob, Chow Theis Recovery	1,630- 6,300	9.0	180- 700
50 NE	Theis, Jacob, Chow Theis Recovery	5,600- 9,400	9.0	620-1,040
100 NE	Theis, Jacob, Chow Theis Recovery	8,800-17,100	10.0	880-1,710
Well	Theis Recovery	3,900	9.0	430
West line 0-50 ft	Jacob (Drawdown vs log distance)	2,150	9.0	240
50-1000 ft		17,032	15.0	1,135
Northeast line 0-80 ft	Jacob (Drawdown vs log distance)	2,238	9.0	250
80-100 ft		11,480	10.5	1,090

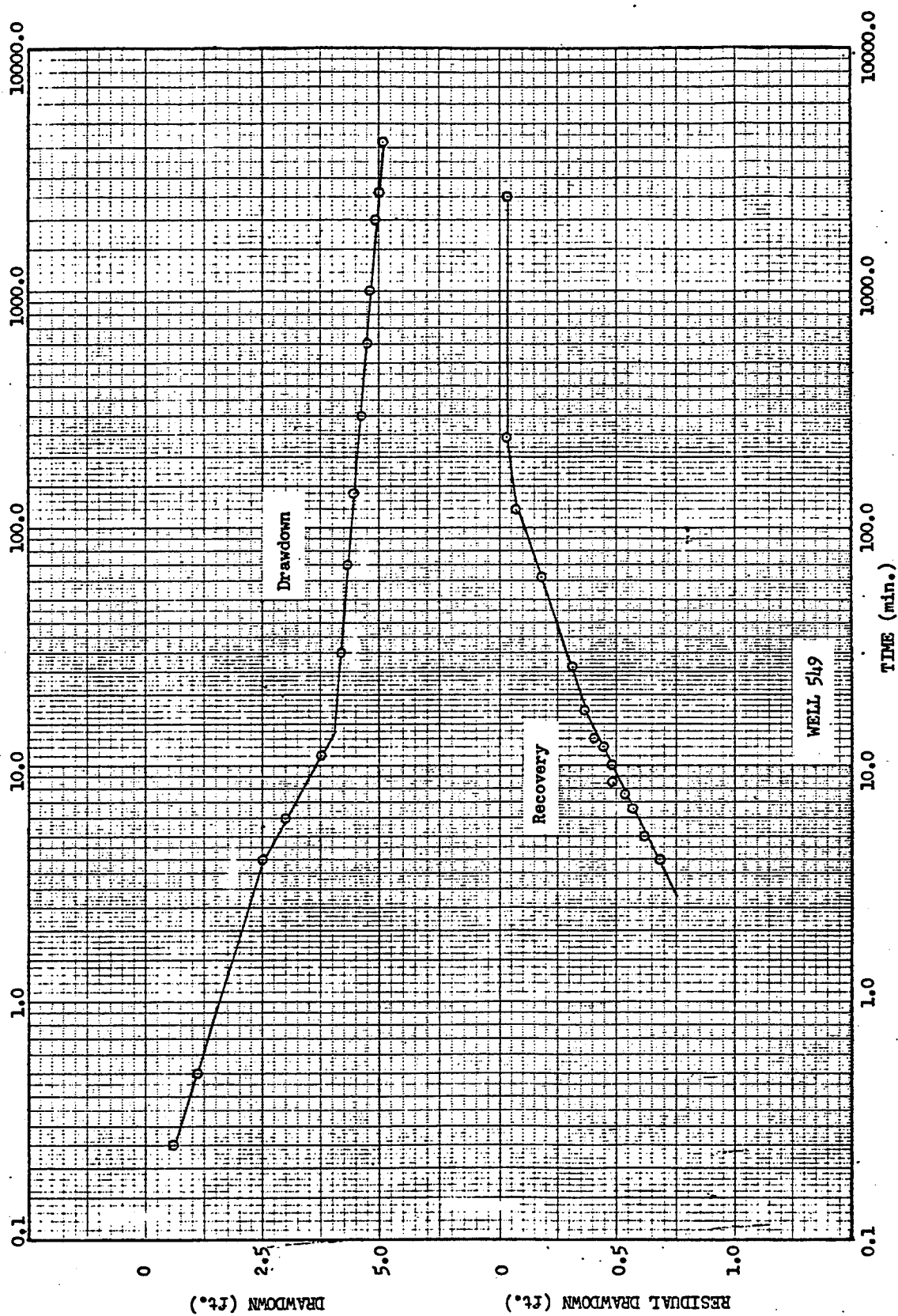


Figure 68. Drawdown and recovery versus time, Well 549

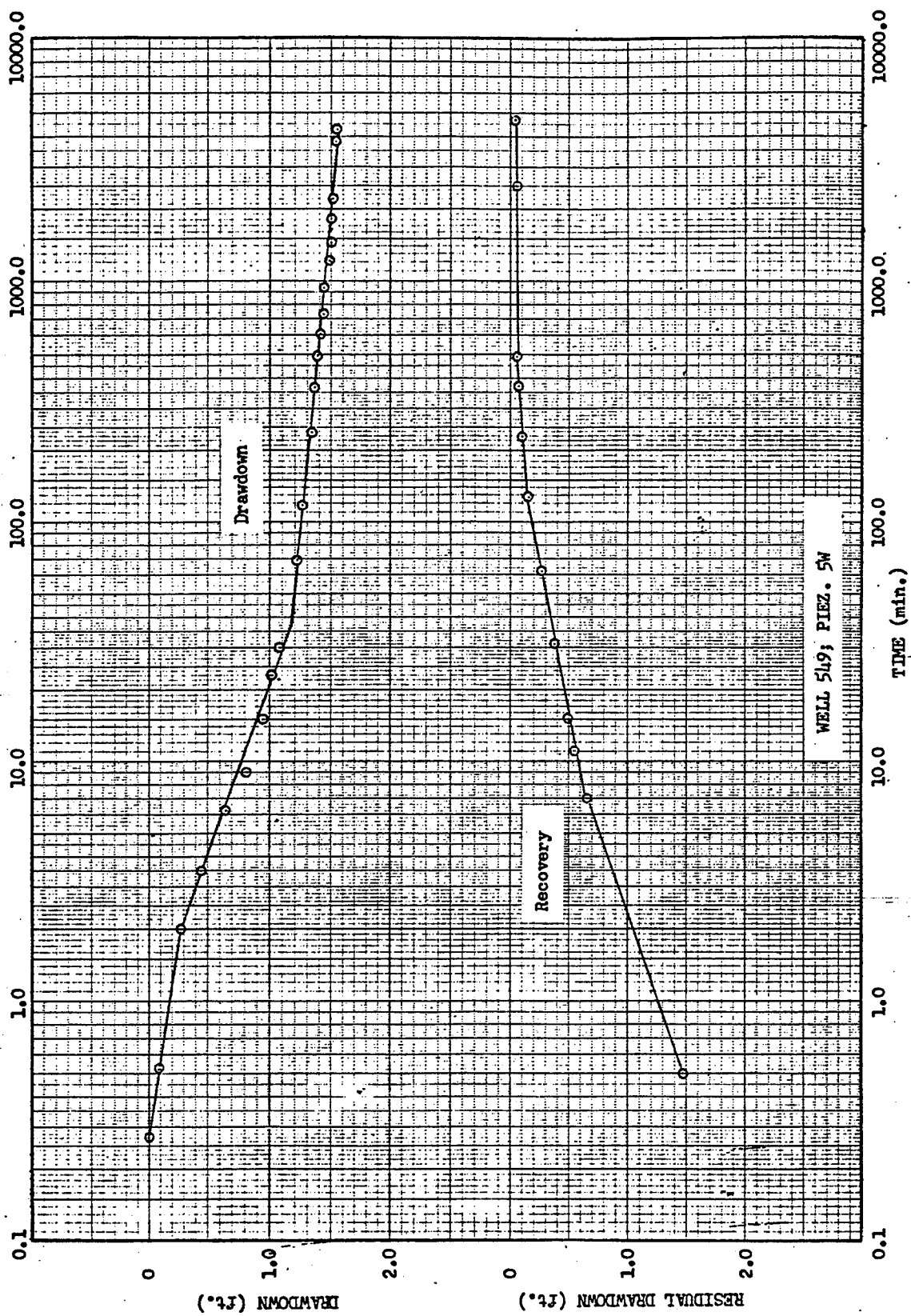


Figure 69. Drawdown and recovery versus time, Well 549; Piezometer 5W

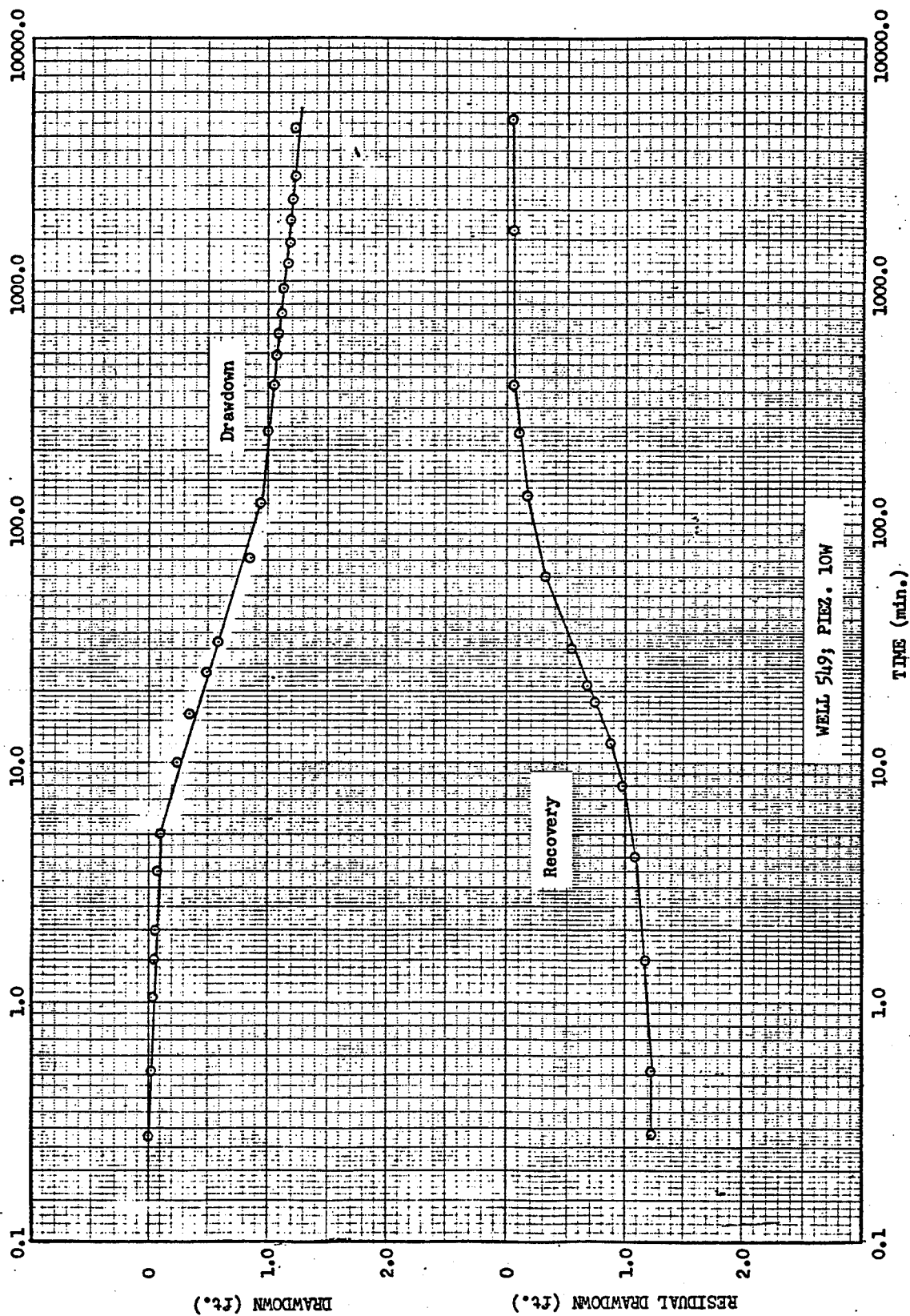


Figure 70. Drawdown and recovery versus time, Well 549; Piezometer 10W

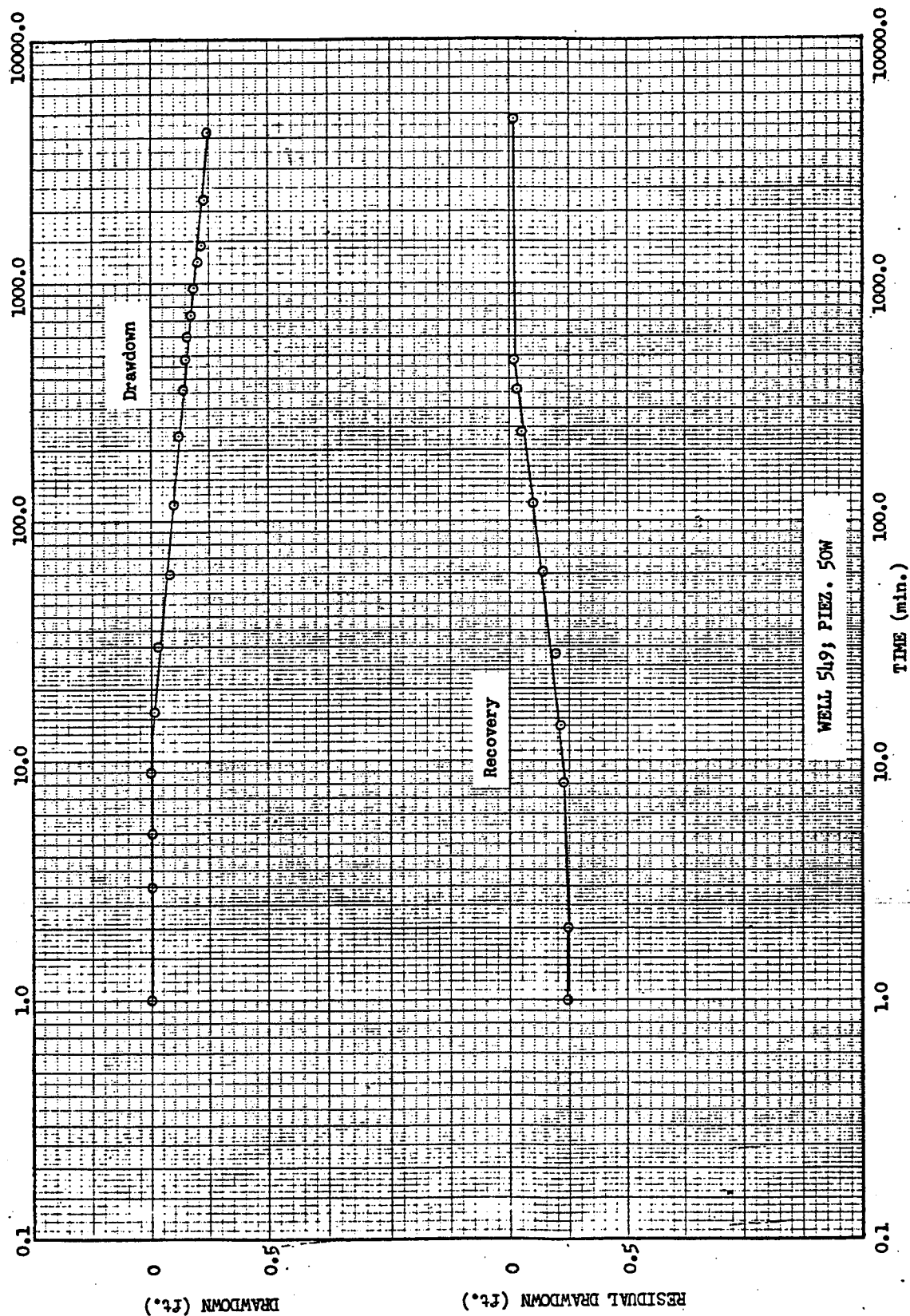


Figure 71. Drawdown and recovery versus time, Well 549; Piezometer 50W

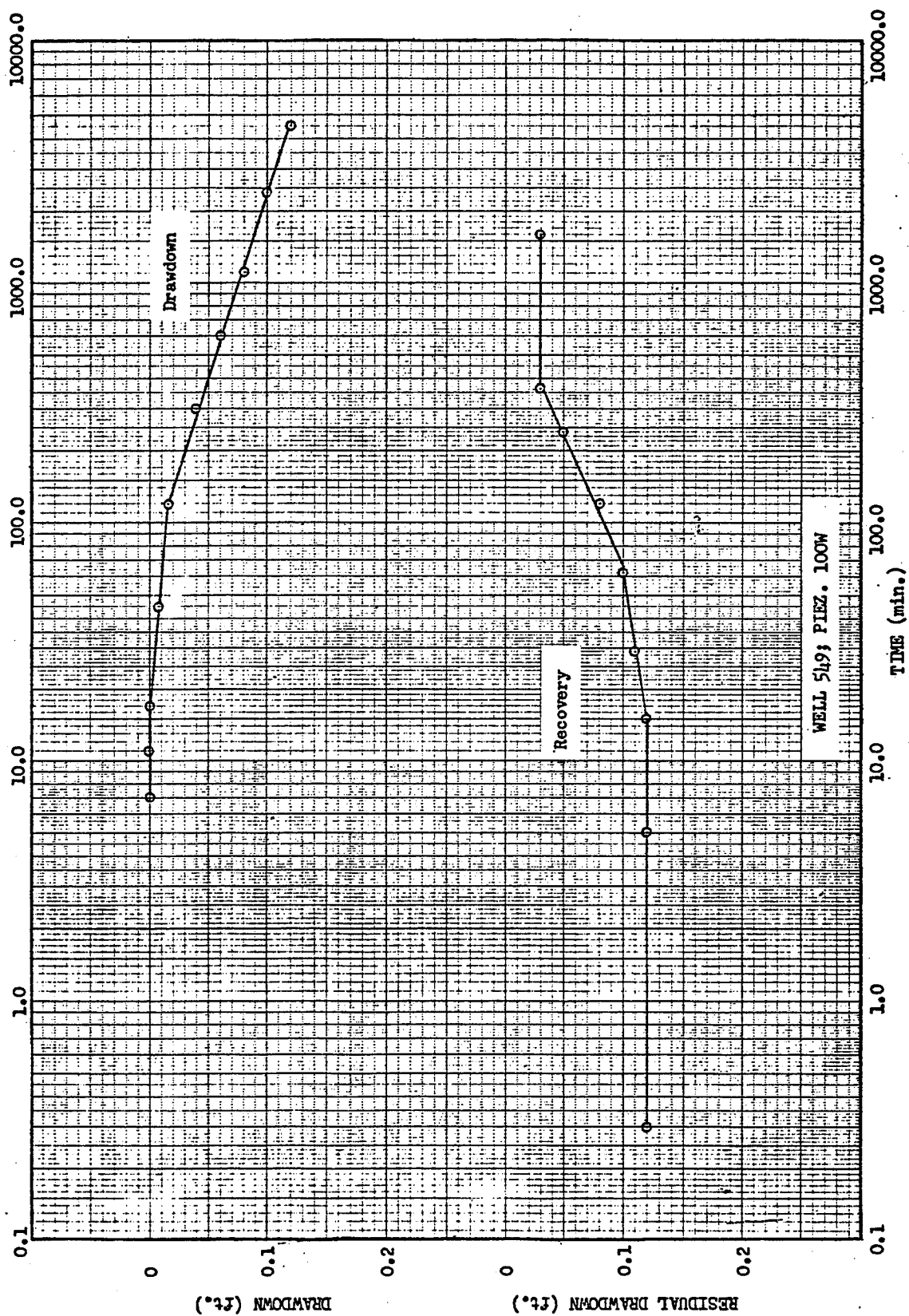


Figure 72. Drawdown and recovery versus time, Well 549; Piezometer 100W

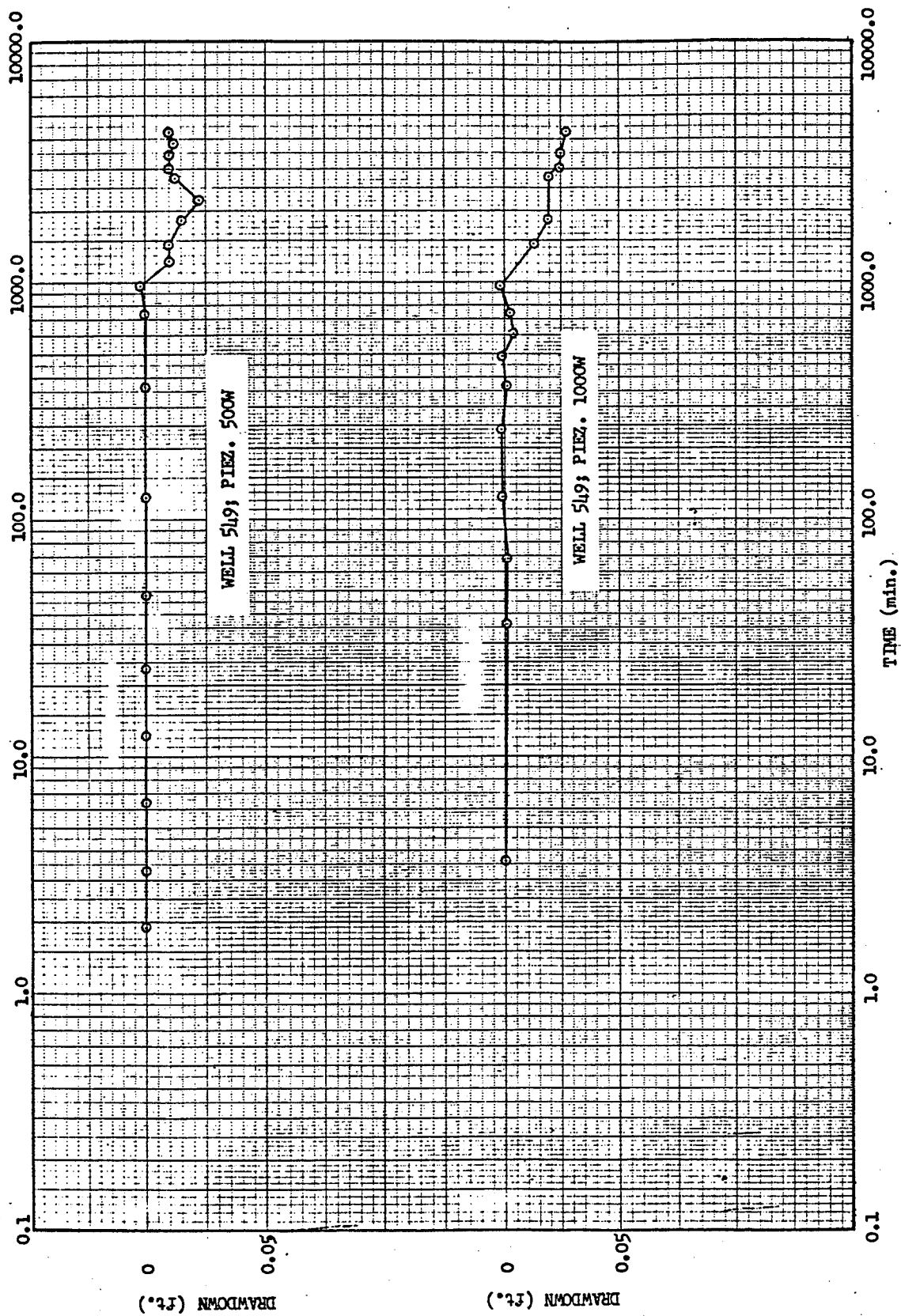


Figure 73. Drawdown versus time, Well 549; Piezometers 500W and 1000W

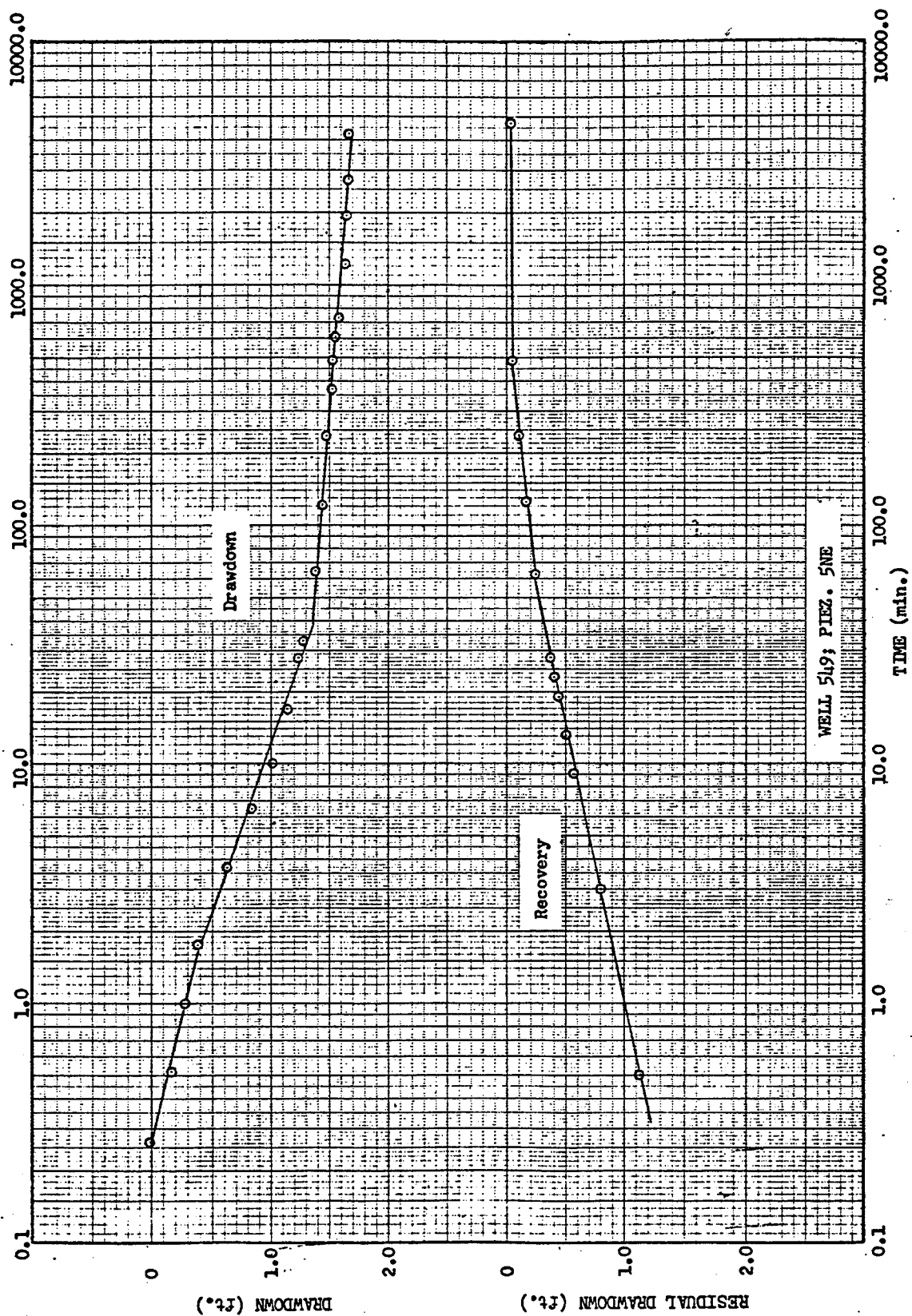


Figure 74. Drawdown and recovery versus time, Well 549; Piezometer 5NE

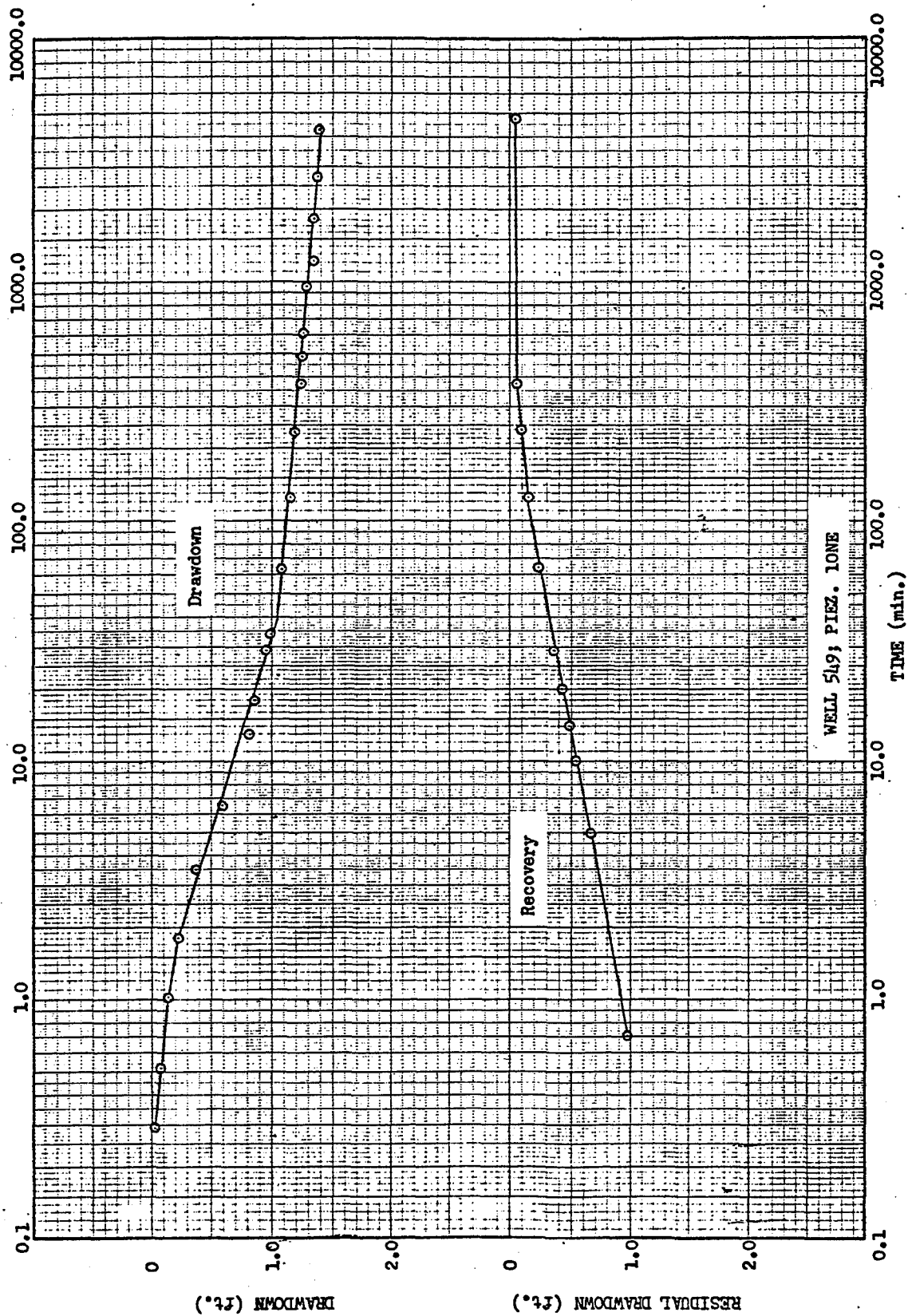


Figure 75. Drawdown and recovery versus time, Well 549; Piezometer 10NE

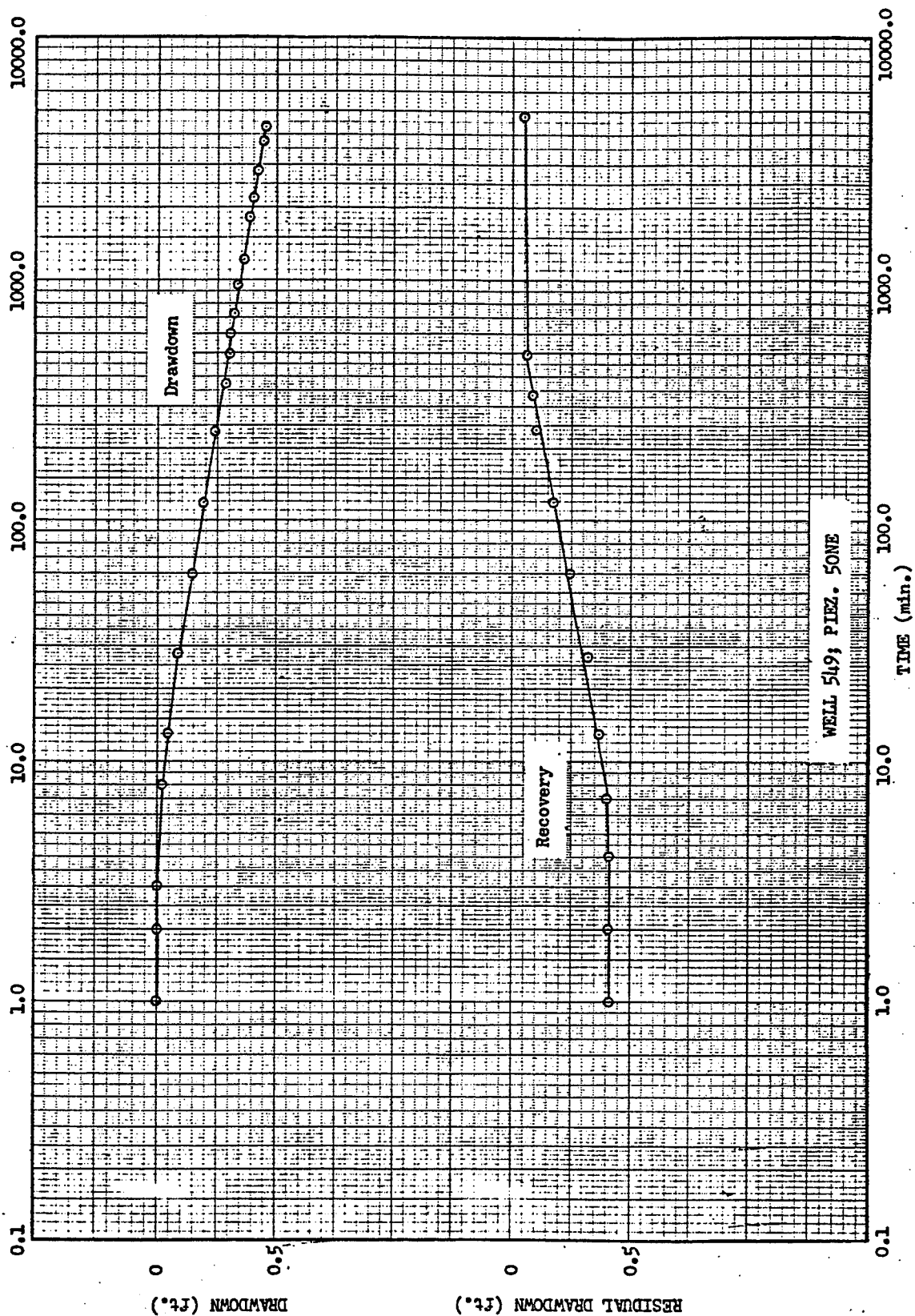


Figure 76. Drawdown and recovery versus time, Well 549; Piezometer 50NE

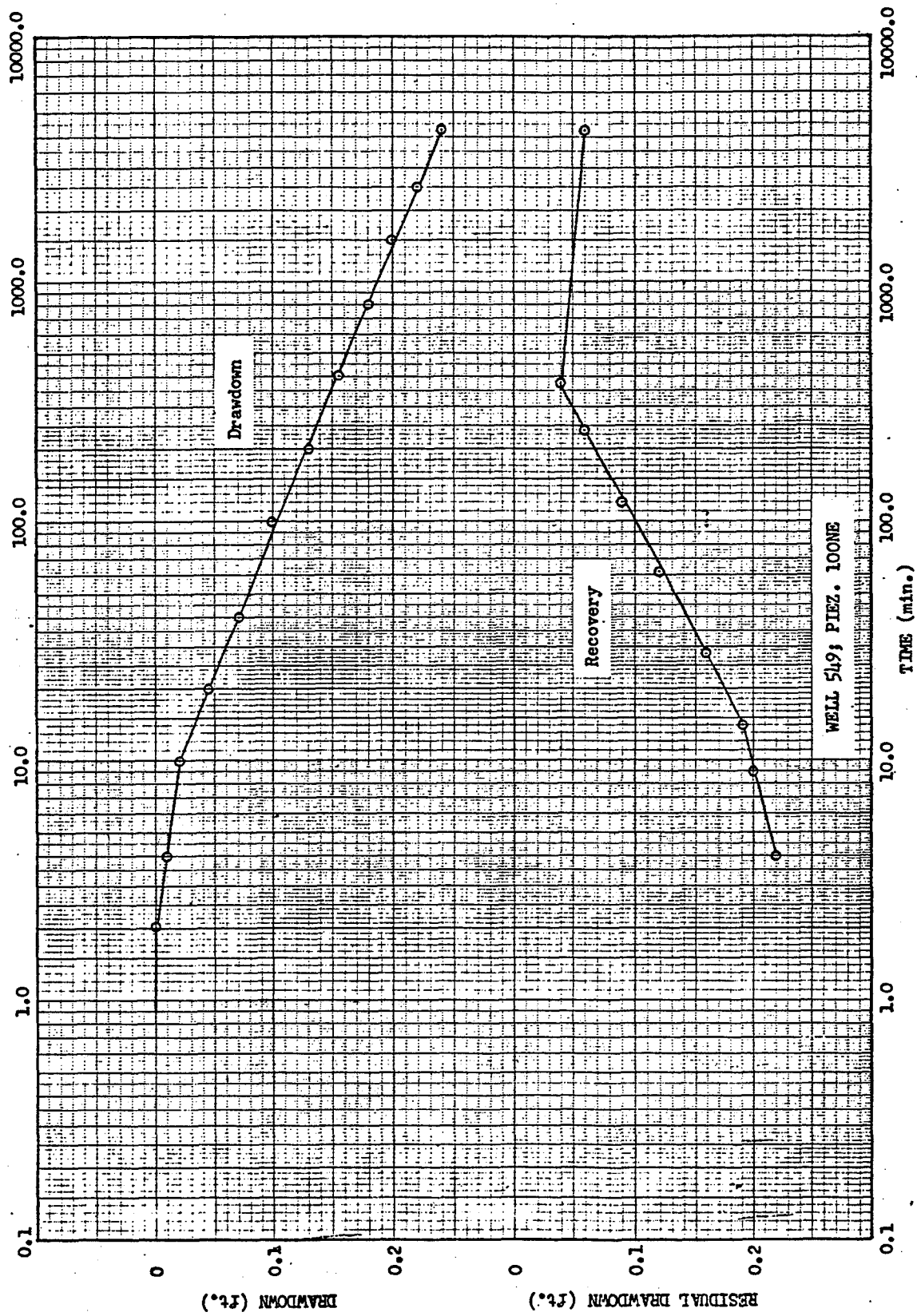


Figure 77. Drawdown and recovery versus time, Well 549; Piezometer 100NE

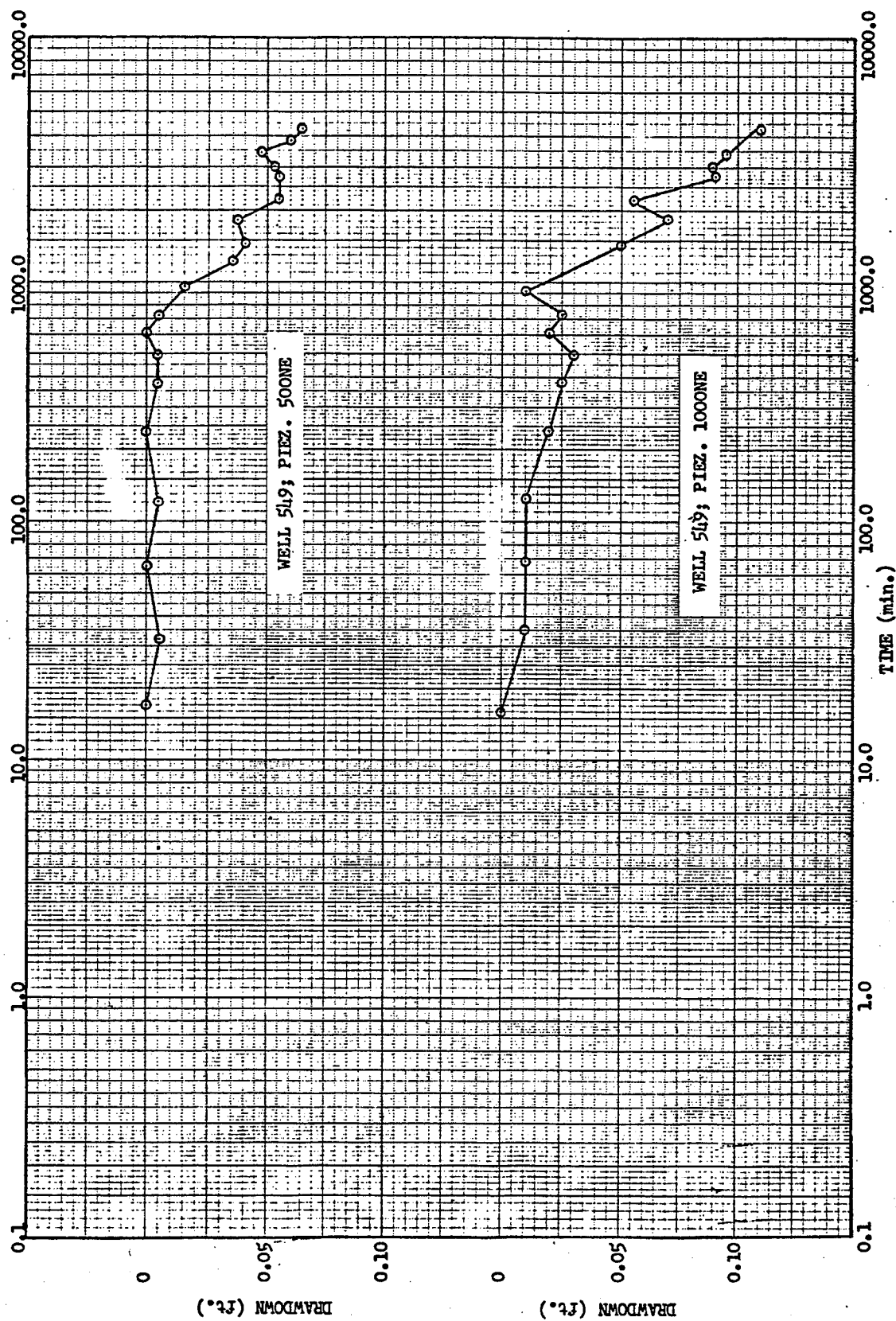


Figure 78. Drawdown versus time, Well 549; Piezometers 500NE and 1000NE

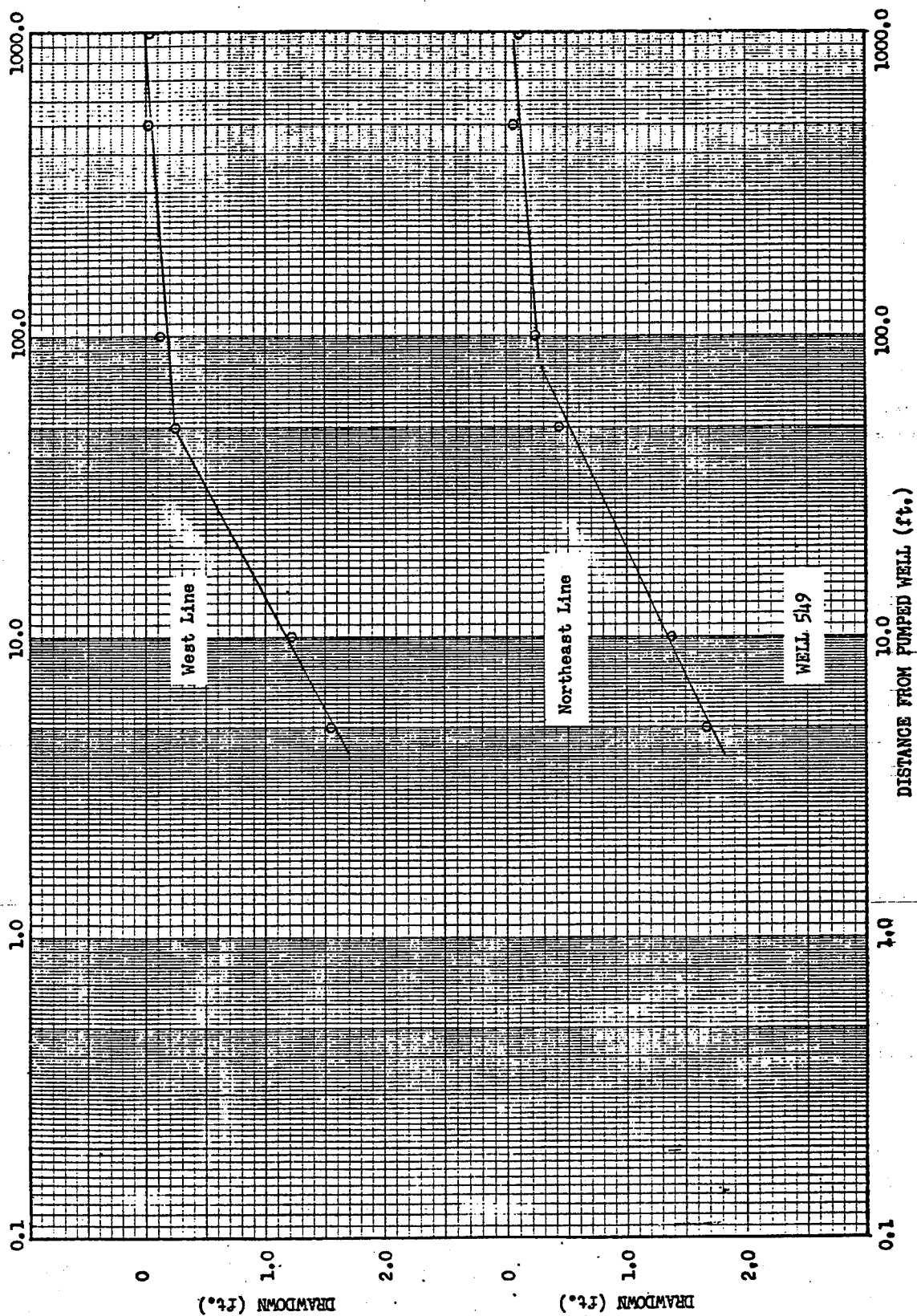


Figure 79. Drawdown versus distance from pumped well, Well 549